Water Resources Research

RESEARCH ARTICLE

10.1002/2016WR019767

Special Section:

Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems

Key Points:

- Pronounced redistribution of water stress driven by spatially distributed sectoral water demands managed through groundwater and return flow
- East-West contrast due to differences in regional sectoral water use, allocation, hydroclimatology, and storage capacity.
- Sectoral water management is essential for the coupling of integrated assessment models with Earth system models

Supporting Information:

- Supporting Information S1

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Citation:

Voisin, N., M. I. Hejazi, L. R. Leung, L. Liu, M. Huang, H.-Y. Li, and T. Tesfa (2017), Effects of spatially distributed sectoral water management on the redistribution of water resources in an integrated water model, *Water Resour. Res.*, 53, 4253–4270, doi:10.1002/2016WR019767.

Received 9 SEP 2016

Accepted 28 APR 2017

Accepted article online 8 MAY 2017

Published online 25 MAY 2017

Effects of spatially distributed sectoral water management on the redistribution of water resources in an integrated water model

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Abstract Realistic representations of sectoral water withdrawals and consumptive demands and their allocation to surface and groundwater sources are important for improving modeling of the integrated water cycle. To inform future model development, we enhance the representation of water management in a regional Earth system (ES) model with a spatially distributed allocation of sectoral water demands simulated by a regional integrated assessment (IA) model to surface and groundwater systems. The integrated modeling framework (IA-ES) is evaluated by analyzing the simulated regulated flow and sectoral supply deficit in major hydrologic regions of the conterminous U.S., which differ from ES studies looking at water storage variations. Decreases in historical supply deficit are used as metrics to evaluate IA-ES model improvement in representing the complex sectoral human activities for assessing future adaptation and mitigation strategies. We also assess the spatial changes in both regulated flow and unmet demands, for irrigation and nonirrigation sectors, resulting from the individual and combined additions of groundwater and return flow modules. Results show that groundwater use has a pronounced regional and sectoral effect by reducing water supply deficit. The effects of sectoral return flow exhibit a clear east-west contrast in the hydrologic patterns, so the return flow component combined with the IA sectoral demands is a major driver for spatial redistribution of water resources and water deficits in the US. Our analysis highlights the need for spatially distributed sectoral representation of water management to capture the regional differences in interbasin redistribution of water resources and deficits.

1. Introduction

Human activities associated with water use (e.g., irrigation), reservoir operation, and groundwater pumping can induce pronounced effects on water resources availability and streamflows. Postel *et al.* [1996] estimated that 26% of global evapotranspiration is associated with human activities, and 56% of spatially and temporally available global runoff is withdrawn from water bodies. Also, unsustainable groundwater depletion to supplement surface water supply is a wide-spread practice across the globe, so about a third of Earth's largest groundwater aquifers are being rapidly depleted by human consumption [Wada *et al.*, 2012, 2014; Richey *et al.*, 2015]. Recognizing the critical role of water in human-Earth system interactions, the integrated assessment (IA) community is moving to incorporate water within their modeling frameworks [e.g., Davies *et al.*, 2013; Hejazi *et al.*, 2013, 2014a, 2014b; Kyle *et al.*, 2013; Blanc *et al.*, 2014; Liu *et al.*, 2015; Kim *et al.*, 2016]. At the same time, the Earth System (ES) modeling community is incorporating human activities such as irrigation schemes [Sacks *et al.*, 2009; Leng *et al.*, 2013], reservoir operations [Voisin *et al.*, 2013a, 2013b], and groundwater pumping [Leng *et al.*, 2014; Zou *et al.*, 2014; Pokhrel *et al.*, 2015] in land surface models. Coupled modeling experiments with interactions between IA and ES models to take advantage of the richer representation of human and physical processes in the two types of models, respectively, are only emerging [Hejazi *et al.*, 2015].

The impacts of water management are scale dependent so the representation of water management in ES modeling studies must be appropriate for the scientific questions to be addressed. Supporting information Table S1 summarizes approaches for representing water management in ES models which tend to either

focus on local feedbacks into the atmosphere and water column, or on large-scale water storage variations. In this paper, we focus on water management representation approach that prioritizes water resources transfers over large domains and that is useful for evaluating climate change adaptation strategies. This paper builds on recent advances in IA and ES modeling to better understand and represent the human-natural system feedbacks. More specifically, we aim to investigate how spatially distributed sectoral water demands and allocation to groundwater system influence water management, leading to spatial redistribution of water resources and detection of water stressed regions. The specific coupling of IA with ES models through sectoral water demands as input has implications to ES modeling that need to be evaluated (supporting information Table S1). Specifically, groundwater and return flow emerge as important components that must be included in ES models to handle the complex representations of water demand from IA models, which include spatially distributed sectoral withdrawal and consumptive water demands, and sectoral allocation to surface and groundwater systems [Kim *et al.*, 2016]. A second implication of using IA is the evaluation approach to account for supply deficit (i.e., unmet water demands) rather than water storage, which is the typical focus of ES evaluation. The supply deficit is a useful metric for analysis of coupled IA-ES simulations to evaluate adaptation and mitigation strategies under climate change conditions [Hejazi *et al.*, 2015].

Some large-scale ES studies already represent groundwater and return flow components [Döll *et al.*, 2012; Wada *et al.*, 2014; Pokhrel *et al.*, 2015] (supporting information). In these studies, irrigation water demand is usually computed using a land surface model and corresponds to the evaporative demand from irrigated croplands [Döll *et al.*, 2012; Pokhrel *et al.*, 2015]. The consumptive irrigation water demand is then optionally inflated to a withdrawal demand using a country-specific ratio (consumptive over withdrawal ratio) from Döll and Siebert [2002] or obtained from the AQUASTAT database from the Food and Agriculture Organization (http://www.fao.org/nr/water/aquastat/water_use_agr/index.stm). Nonirrigation water demands are provided by country-specific reported estimates of domestic and industrial demand from AQUASTAT while allocation of water demands to surface and groundwater systems are derived using a combination of AQUASTAT and the International Groundwater Resources Assessment Center (IGRAC) [Wada *et al.*, 2010, 2014]. In this data-driven approach for representing nonirrigation water demands, assessment of future changes in water resources usually assumes no change in nonirrigation water demands [e.g., Wander *et al.*, 2015], which may limit our understanding of human influence and its feedbacks.

Moreover, models that limit demands to surface water resources alone tend to exaggerate water stress [Voisin *et al.*, 2013a; Pokhrel *et al.*, 2012; Haddeland *et al.*, 2006], so more realistic representations of the sources of sectoral water supply and accounting for return flow are important for improving modeling of the interactions between human activities and surface hydrology [Döll *et al.*, 2012; Wada *et al.*, 2014; Pokhrel *et al.*, 2015]. Previous research efforts have focused on the distribution of irrigation water demand between surface and shallow aquifers [Condon and Maxwell, 2015, 2014a, 2014b; Leng *et al.*, 2014; Wada *et al.*, 2014], or surface and groundwater as a whole [Biemans *et al.*, 2011]. de Graaf *et al.* [2014] and Wada *et al.* [2014] explored a dynamic allocation of total demand to aquifers based on water availability. Pokhrel *et al.* [2015] improved the global integrated modeling framework by representing groundwater dynamics for pumping purposes rather than assuming that unmet irrigation demand was met by unsustainable groundwater by default. In addition to more complex groundwater representations, the allocation of sectoral water demands to surface and deep groundwater systems affects the modeling of water stress. Some studies assumed that water demands that cannot be met by the surface water system (or surface and shallow aquifer) are unconditionally met by a hypothetical, unlimited source of deep groundwater [Hanasaki *et al.*, 2008a, 2008b; Biemans *et al.*, 2011; Pokhrel *et al.*, 2012; Wada *et al.*, 2014; Pokhrel *et al.*, 2015]. In Döll *et al.* [2012], a specified fraction of sectoral water demand is to be met by the land surface scheme (surface and shallow aquifer) while the remaining is allocated to a very large groundwater storage. Supply deficit, or inability of the land surface model to fulfill the water demand, is allowed but not accounted for. Pokhrel *et al.* [2015] reported that the use of unsustainable water demand accounts for 21% of the total demand globally and is comparable to the 18% supply deficit in Döll *et al.* [2012]. The analyses and validation discussed in previous studies focused on the changes in terrestrial water storage and the definition of water scarcity as regions with significant “groundwater or terrestrial water storage depletion.”

On modeling return flow, previous efforts have looked into withdrawals versus consumptive use demand. Biemans *et al.* [2011] introduced a country-specific factor to differentiate withdrawal and consumptive

irrigation demand. Pokhrel *et al.* [2012] and Döll *et al.* [2012] expanded on withdrawals to consumptive use factors, and added nonirrigation uses in the system using country scale consumptive over withdrawal ratio. de Graaf *et al.* [2015] concluded that both sectoral partitioning between withdrawals versus consumptive water demand and groundwater versus surface water supply would further improve their modeling framework.

In this study, we leverage the integrated modeling framework of Hejazi *et al.* [2015], which consists of a regional integrated assessment model that includes a water demand model, a regional Earth system model, and a coupled hydrology, water management, and river routing model. By integrating a regional IA and ES, the integrated modeling framework can facilitate the opportunity to assess different adaptation and mitigation strategies and their implications on water resources and water deficits. For example, by using GCAM coupled to CLM-MOSART-WM, Hejazi *et al.* [2015] investigated the implications of two future scenarios with and without mitigation (i.e., RCP8.5 versus RCP4.5) to assess water deficits in the US at regional scale. They found that irrigation water use associated with bioenergy production in RCP4.5 increases water deficit over RCP8.5, despite larger warming and evapotranspiration in the latter that generally reduces runoff. Similar experiments can be performed with the updated modeling framework to explore how different mitigation strategies (e.g., RCPs), socioeconomic pathways (e.g., SSPs), and/or adaptation measures may affect regional water resources and the induced effect of return flow and groundwater pumping processes on redistributing water in space and time. We extend our integrated modeling framework that includes spatially distributed sectoral water demands simulated by an IA model with simple representations of groundwater use and return flow modules. Supporting information Table S1 provides a comparison of modeling approaches/assumptions used in benchmark ES studies [Döll *et al.*, 2012; Pokhrel *et al.*, 2015; Condon and Maxwell, 2014b] with the coupled IA-ES framework used in this study. We perform numerical experiments to test our hypothesis that sectoral return flow from the surface and groundwater systems can redistribute water in space, and the reclaiming or recycling of water resources can have a pronounced effect on the integrated IA-ES water modeling results toward future development of adaptation and mitigation strategies. It differs from other ES-oriented studies in that: first we evaluate the modeling framework and sectoral management through regulated flow but also supply deficit instead of water storage variations (see supporting information). A decrease in supply deficit in water stressed region relative to a benchmark is a demonstration of improvement toward a more realistic representation of human activities in ES models [Voisin *et al.*, 2013b; Hejazi *et al.*, 2015; Voisin *et al.*, 2016]. A second aspect of the analysis is to look at the spatial patterns in regulated flow and supply deficit to understand the benefit of using spatially distributed information on human activities, which is provided by integrated assessment models and differ from country-specific data.

2. Modeling Framework

The modeling framework leverages an existing integrated water modeling system consisting of a regional integrated assessment model with a detailed representation of water demand sectors, a land surface hydrology model, a river routing model and a water resources management model as applied in Hejazi *et al.* [2015] and shown in Figure 1. The framework has been extended to include modules for groundwater as a source of supply and return flow. In this study, water withdrawal is defined as the total amount of water that is taken from a water body, whereas water consumption corresponds to the amount of water withdrawal that is not returned to the original source and no longer available for reuse (i.e., water is consumed through evaporation or incorporated into products or waste materials) [Vickers, 1999].

2.1. Regional Integrated Assessment Model

A regional integrated assessment model is used to provide gridded water demands estimates by end-use sector. The GCAM-USA model adds regional details in the US in the Global Change Assessment Model (GCAM), which is a global integrated assessment model focused on long-term trends in energy, land use, and greenhouse gas emissions [Edmonds and Reilly, 1983; Kim *et al.*, 2006]. In GCAM-USA, the 50 US states plus the District of Columbia are included as explicit regions that operate within the global GCAM model [Zhou *et al.*, 2013; Liu *et al.*, 2015; Hejazi *et al.*, 2015]. GCAM-USA, hereafter simply called GCAM, includes a detailed representation of six water demand sectors (irrigation requirements at ten agroecological units, domestic, manufacturing, and electricity generation at the State level, livestock, and primary energy at

Figure 1. The overall modeling framework with model components (pink) including the global Earth system model (CESM), regional Earth system model (RESM), integrated assessment model (GCAM-USA), and land surface and river models (CLM/MOSART). Input and output data for the models are shown in green, together with the brown arrows showing the flow of information.

ing for hydrologic simulations. The RESM uses large-scale boundary conditions from a historical simulation by the Community Earth System Model (CESM) [Gent et al., 2011] as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) for 1975–2004. The RESM simulation was performed at 20 km grid resolution over North America. The simulated temperature and precipitation were bias corrected following the Bias Correction-Spatial Disaggregation (BCSD) approach described in Wood et al. [2004] based on a gridded observation data at 1/8° resolution (<http://www.hydro.washington.edu/SurfaceWaterGroup/Data/gridded/index.html>). The simulated solar fluxes were bias corrected by subtracting the long-term mean bias based on the North America Land Data Assimilation System (NLDAS-2) forcing data (<http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php>).

2.3. Community Land Model (CLM)

CLM4 is the land component of the Community Earth System Model (CESM) (formerly known as the Community Climate System Model (CCSM)) [Gent et al., 2010; Lawrence et al., 2011]. In this study, CLM4 was configured to run at 1/8° resolution with soil, vegetation, and land cover characteristics of the study domain derived from the 0.05° input data set developed by Ke et al. [2012], in which soil information was extracted from the 30 arc sec State Soil Geographic Database (STATSGO, now referred to as the US General Soil Map) [Miller and White, 1998]. The meteorological variables from the bias-corrected RESM downscaled simulations

national scale) and tracks them at multiple spatial scales and annual scale [Hejazi et al., 2013, 2014a, 2014b; Davies et al., 2013; Kyle et al., 2013; Chaturvedi et al., 2015; Liu et al., 2015].

The sectoral (irrigation and nonirrigation) water demand results were both spatially and temporally downscaled to be consistent with the spatial and temporal resolutions of other models (CLM, MOSART, and WM) described below. Annual sectoral water demands were calibrated with respect to USGS reported water demand [Kenny et al., 2009]. The procedure for the downscaling and its evaluation against observations were documented in Voisin et al. [2013a] and Hejazi et al. [2014b, 2015]. Figure 2 shows the annual spatial distribution of GCAM water demand by sector and the allocation of the demands to surface and groundwater systems. For contributing area in Canada and Mexico, sectoral water demands were provided using the global version of GCAM [Hejazi et al., 2014b] and used as in Voisin et al. [2013a]. All the demands are allocated to the surface water system and a default country-specific consumptive over withdrawal demand ratio is used over the areas (Figure 2).

2.2. Regional Earth System Model (RESM)

A regional Earth system model (RESM) [Ke et al., 2012; Gao et al., 2014] that couples the Weather Research and Forecasting (WRF) model [Skamarock et al., 2008] with the Community Land Model (CLM) [Lawrence et al., 2011] is used to provide meteorological forcing

Figure 2. Characteristics of the GCAM water demand forcing combined with USGS [Kenny *et al.*, 2009] distribution of the water demand to surface and groundwater systems used in the water management model for different modeling experiments over the U.S. Units are cubic meter per day per grid cell (1/8th latitude-longitude).

were converted to the CLM input format to drive the simulations at hourly time steps. The model was spun up by repeating the meteorological forcing over the historical period (i.e., 1975–2004) until all state variables, including soil moisture, soil temperature, and groundwater table depth, reached an equilibrium, after which model outputs were saved to initialize the CLM4 simulation over the 1985–2004 (historical) period.

2.4. Water Management (WM) Model

A large-scale water management model (WM) [Voisin *et al.*, 2013b] with a 1/8° daily representation is used to allocate grid cell water demands and manage reservoir releases and storage. WM relies on generic operating rules that mimic monthly releases and storage patterns based on the objectives of the reservoir similar to Hanasaki *et al.* [2006], Biemans *et al.* [2011], Döll *et al.* [2012], and Pokhrel *et al.* [2012, 2015], and prescribes nonirrigation water demand to be met before irrigation demand. There are 1848 reservoirs in the conterminous United States that are explicitly modeled in this study, which are broken up by their primary use into four categories: flood control, irrigation, flood control with irrigation, and other uses. Reservoir releases are managed to support dependent grid cells which cannot meet their demand with their local supply [Voisin *et al.*, 2013b; Döll *et al.*, 2012]. The dependency database [Voisin *et al.*, 2013b] associates each individual dam with all the grid cells that are downstream of the dams and within reach of the stream, i.e., they have to be at a lower elevation than the grid cell where the dam is located, and have to be within a 100 km buffer area of the stream impounded by the dam. The size of the buffer zone is arbitrary and a size of 250 km would lead to a 3% increase in global annual water withdrawal [Biemans *et al.*, 2011]. Following the work of Voisin *et al.* [2013a, 2013b], the monthly release and storage targets are precomputed individually for each reservoir based on long-term historical mean monthly inflow and demand, the reservoir storage characteristics and purpose. Actual releases are adjusted monthly for interannual variability in the releases, and daily for spilling and meeting minimum flow requirements (environmental flow requires minimum release of 10% of mean monthly natural flow which also constrains withdrawals). The reservoir model is coupled to the Model for Scale Adaptive River Transport (MOSART) [Li *et al.*, 2013, 2015] to route the regulated flow from reservoirs to downstream channels and the adjusted local runoff within each grid cell. The MOSART-WM model uses the CLM simulated runoff and baseflow for 1982–2004, and GCAM irrigation and nonirrigation demand as inputs, with 1982–1984 as warm up for WM. Readers are referred to Voisin *et al.* [2013b] for a more detailed description of the model. The model has been applied over the continental US in its gridded 1/8th degree daily representation, linked with GCAM water demand, in the context of historical and future climate and demand [Hejazi *et al.*, 2015]. The existing integrated modeling framework (as described in Hejazi *et al.* [2015]) is further extended to track both groundwater use and return flows for the purpose of this paper as described next. Watershed-scale representation of interaction between groundwater and surface water under water management is complex and includes fine scale dynamics [Maxwell *et al.*, 2015; Condon and Maxwell, 2014a; de Graaf *et al.*, 2015]. To integrate the diverse sectoral water demands from integrated assessment models and water availability from Earth system models, we adopt a simple conceptual representation of groundwater and return flow to explore their impacts and sensitivity, which will guide future development of more relevant processes. Figure 3 presents the overall implementation of groundwater and return flow into the river routing reservoir model component.

2.5. Groundwater Use

Although a groundwater use scheme to withdraw water from unconfined aquifers has been implemented in CLM and evaluated at continental and global scales [Leng *et al.*, 2014, 2015], in this study, we did not account for the dynamic effects of groundwater pumping on the hydrology simulation by CLM. Since MOSART-WM is presently not fully coupled to CLM, an offline implementation (one-way coupling) of groundwater use is employed in this study. To track groundwater use explicitly, the GCAM irrigation and nonirrigation water demands are partitioned into surface and groundwater demands based on predefined fractions derived from observed historical county-based USGS data [Kenny *et al.*, 2009] (supporting information Table S1). For example, the sectoral groundwater demand at a given location is estimated as the ratio of the 2005 USGS reported groundwater withdrawal to the 2005 reported sectoral freshwater withdrawal multiplied by the sectoral water demand estimates from GCAM for a given grid (equation (1))

$$C_{gw\text{sector}}(lat, lon, t) = C_{GCAM\text{sector}}(lat, lon, t) \cdot \left[\frac{USGS_{\text{groundwater}}}{USGS_{\text{total}}} \right]_{\text{sector}} \quad (1a)$$

$$C_{sfce\text{sector}}(lat, lon, t) = C_{GCAM\text{sector}}(lat, lon, t) \cdot \left[\frac{USGS_{\text{surface water}}}{USGS_{\text{total}}} \right]_{\text{sector}} \quad (1b)$$

where C_{gw} and C_{sfce} are the fractions of the consumptive use water demand from GCAM allocated to the groundwater and surface water systems, respectively. $USGS_{\text{groundwater}}$, $USGS_{\text{surface water}}$, and $USGS_{\text{total}}$ are the USGS groundwater, surface water, and total freshwater withdrawals, respectively, reported in 2005 by

Figure 3. Conceptual diagram representing the interaction of the groundwater and return flow component within the integrated water model.

county in *Kenny et al. [2009]*. Note that there is a sector specific USGS ratio for irrigation and nonirrigation sectors applied to sector specific GCAM consumptive use demand. Figure 2a shows the fraction of water demand that is assigned to surface water at the grid scale as derived from the USGS data. These fractions are held constant over the historical simulation. Also demands allocated to groundwater supply are assumed to be always met.

A constant fractional allocation of sectoral demand to groundwater in times of drought is not a realistic assumption [Faunt and Sneed, 2015; Jones, 2015]. It is however to be evaluated with respect to a similar assumption used in other large-scale studies [Döll *et al.*, 2012, and other] using the Siebert *et al.* [2010] sectoral allocation. Pokhrel *et al.* [2015] used a more dynamic relative allocation with all the water demand first allocated to the local surface water system, and the remaining demand allocated to the local groundwater system (supporting information Table S1). This dynamic assumption can be more realistic in times of drought although it might also be unrealistic in regions with environmental constraints on the use of surface water system. The temporally constant but sectorally and spatially distributed allocation used in this analysis supports our objective to evaluate the coupling of IA with ES and the overall water management representation realism at a spatial scale finer than large river basins.

The total met consumptive water demand (D_{met}) is the sum of the met consumptive use allocated to the surface system and the consumptive use allocated to the groundwater system

$$D_{\text{met}} = F \cdot C_{\text{sfce}} + C_{\text{qgw}} \quad \text{with } F \in [0, 1] \quad (2)$$

where F is the fraction of the surface water consumptive use demand met by the integrated water model. Hence the relative supply deficit (RSD) is calculated as follows:

$$RSD = \frac{(1-F) \cdot C_{sfce}}{C_T} \quad (3)$$

where C_T is the sum of C_{sfc} and C_{gw} . The unlimited groundwater used to meet groundwater-allocated demand (total demand minus the demand assigned to the surface water system) in this paper is generally consistent with other large-scale groundwater modeling approaches [Döll *et al.*, 2009, 2012; Biemans *et al.*, 2011; Wada *et al.*, 2011; Pokhrel *et al.*, 2012]. One distinction, however, is that in most of these other studies groundwater is assumed to also satisfy the fraction of water demand that is unmet by surface water resources (equation (3)) [Biemans *et al.*, 2011; Wada *et al.*, 2011; Pokhrel *et al.*, 2012] (supporting information Table S1). In this study, similar to Döll *et al.* [2012], the groundwater component relieves the surface water system in order to represent a realistic surface water system supply deficit. We evaluate this supply deficit while Döll *et al.* [2012] focused on the implied groundwater storage variations. The tracking of groundwater use in our approach permits the modeling framework to track the unconsumed portion of the extracted groundwater that is expected to return back to the system with the return flow component presented next.

2.6. Return Flow

The return flow module in WM requires both withdrawals (W) and consumptive use (C) for both irrigation and nonirrigation sectors from GCAM, which are further allocated to groundwater and surface water systems using equation (1). At each time step, WM first attempts to meet nonirrigation withdrawal allocated to the surface water system using local storage (runoff, baseflow, main channel), then irrigation withdrawals. Any unmet demand is then allocated to reservoirs to which the specific grid cell is dependent (upstream reservoirs if the grid cell is within 100 km distance of the impounded reach, *Voisin et al.* [2013b]), with the same sectoral priority. The potential sectoral return flow within that grid cell is the difference between sectoral withdrawals and consumptive use from both surface water and groundwater systems (equation (4)). This is consistent with *Döll et al.* [2012] and is to be differentiated from *Pokhrel et al.* [2015] who complement the local surface water system supply with local groundwater instead of surface water system diversion from reservoirs, i.e., nonlocal (supporting information Table S1).

$$R_{gw} = W_{gw} - C_{gw} \quad (4a)$$

$$R_{sfce} = W_{sfce} - C_{sfce} \quad (4b)$$

where W_{gw} and W_{sfce} stand for groundwater and surface water withdrawals, respectively. R_{gw} is the potential return flow to the surface water system from groundwater management. R_{sfce} is the potential return flow to the surface water system based on surface water management. Note, the actual groundwater return flow is equal to the potential return flow from groundwater allocation because the demand allocated to the groundwater system is always met. The actual surface water return flow is the potential surface return flow adjusted by the fraction of withdrawal actually met. The total sectoral return flow (R_{total}) is the sum of both sources, including the groundwater contribution, i.e.,

$$R_{total} = F \cdot R_{sfce} + R_{gw} \quad (5)$$

The unconsumed water is returned to the grid cells where withdrawals are distributed. We assume that the return flow from the irrigation sector returns to the surface water system, which causes a delay for the return flow to enter the main channel. Return flow from nonirrigation use is added directly to the main channel of the grid cell (Figure 3). Grid cells that are downstream can benefit from the return flow only if they are crossed by that stream, or a reservoir can capture the return flow and redistribute it. However, we do not take into consideration groundwater aquifer recharge dynamics in this one-way coupling.

3. Experimental Designs

We anticipate that the groundwater and return flow modules may have contrasting local effects: more available supply due to the use of both surface water supply and groundwater versus more stress due to the consideration of withdrawals in addition to consumptive demand. We explore a benchmark and three experiments to understand and quantify the relative contribution of accounting for groundwater use and spatially distributed sectoral consumptive over withdrawals ratios (return flow) to the improvement of the representation of human activities in ES models. The evaluation is based on regulated flow and supply deficit at basin scale as a measure of improvement toward a more realistic representation of human activities in ES models [*Voisin et al.*, 2013b; *Hejazi et al.*, 2015; *Voisin et al.*, 2016]. A second step of the analysis is to look at the spatial patterns in regulated flow and supply deficit to understand the benefit of using spatially distributed information on human activities. In the benchmark experiment, the same modeling framework as in *Hejazi et al.* [2015] is employed with sectoral consumptive water demand passed from GCAM to WM and allocated to the surface water system. To isolate the effects of the groundwater and return flow modules, we conduct two additional experiments, one with the return flow module only (WM_return) and the other one with the groundwater module only (WM_GW). Finally, to better understand the compounding effects of adding the two new modules, we simultaneously account for the effects of groundwater and return flow (WM_GW_return).

In the benchmark experiment, only consumptive demand is allocated to the surface water system. A supply deficit occurs when the surface water supply is below the consumptive demand. The supply deficit is simply equal to the difference between the demand and supply. In the WM_return case, the withdrawal demand (consumptive and nonconsumptive) is allocated to the surface water system. If the surface water supply is

not sufficient to meet the withdrawal demand, the amount of water extracted, which is equal to the available surface water supply, is made available for consumptive and nonconsumptive uses in the same ratio as the consumptive to nonconsumptive demands. The water withdrawn for nonconsumptive use is not available for any other allocation within the same simulation time step and is returned to the stream. In highly allocated basins, the supply deficit in the GW_return case may be higher than the supply deficit in the benchmark case because in the former, the total demand is higher and the deficit is proportionately distributed to the consumptive and nonconsumptive uses, while in the latter, the demand (consumptive only) is lower and more easily met especially for low consumptive to withdrawal ratios (irrigation).

In the WM_GW case, the fraction of consumptive water demand allocated to the groundwater system is unconditionally met, but the fraction of consumptive water demand allocated to the surface water system can be subjected to supply deficit depending on the surface water availability. In the WM_GW_return case, the total consumptive and nonconsumptive demand (withdrawal demand) is allocated to the groundwater and surface water systems based on the same sectoral fraction as in the WM_GW case. The allocation to the surface water system is subjected to supply deficit, which is distributed to consumptive and nonconsumptive uses in the same ratio as the consumptive and nonconsumptive demands, as in the WM_return case.

The differences among the four experiments can illustrate the individual and combined effects of groundwater use and return flow (i.e., water demand allocation, and sectoral water withdrawals and consumptive use), and how the hydrologic spatiotemporal patterns and water resources management (water supply deficit) respond specifically to return flow and groundwater use. The modeling framework is applied over the continental US for the period of 1985–2004.

The original integrated modeling framework (GCAM-CLM-MOSART-WM) has previously been evaluated over the Midwest [Voisin *et al.*, 2013a] and the continental US [Hejazi *et al.*, 2015]. Nazemi and Wheeler [2015a, 2015b] discussed the hydrologic biases in similar large-scale simulations; our relative biases for the benchmark and enhanced WM (i.e., WM_GW_return) simulations are comparable to other large-scale simulations [Haddeland *et al.*, 2006; Biemans *et al.*, 2011; Döll *et al.*, 2012; Wada *et al.*, 2014]. Other studies that did not allow for supply deficit and assumed that the water demand is met by unsustainable groundwater used the groundwater table variation trends for validation [Wada *et al.*, 2014; de Graaf *et al.*, 2015]. In this study, we allow for supply deficit. Therefore meeting the historical water demand is an important metric for model performance and for our objective of evaluating the IA-ES coupling for evaluating adaptation and mitigation strategies in future work. The water demands simulated by GCAM represent well the water withdrawals reported by USGS in 1990 and 2005 [Kenny *et al.*, 2009] with correlation coefficients of 77% and 87%, respectively [Voisin *et al.*, 2013b]. A realistic model should simulate negligible water deficit over a historical period and an improvement in the representation of water management can be measured by a decrease in water supply deficit, if there was any. Figure 4 presents the change in relative supply deficit and therefore the ability to meet the historical water demand with the addition of the groundwater and return flow modules. The implementation of the new module improves the representation of water resources management, as measured by a decreased relative supply deficit. The South-Atlantic-Gulf, Ohio and Upper Mississippi are the only regions with a slight increase. As discussed later, the increase is due to an overall uncertainty in allocation of demand to urban centers, uncertainty in the sources of supply (surface or groundwater), differences between withdrawals and consumptive uses, and uncertainty in the water management model. The new modules therefore improve the representation of water resources management in the IA-ES systems as quantified by supply deficit. The finding is consistent with previous ES studies [Pokhrel *et al.*, 2015; Döll *et al.*, 2012, etc.] which were, however, based on the evaluation of water storage variations.

4. Results

4.1. Spatial Patterns of Water Demands

Figure 2a shows the spatial pattern of the fraction of water demand attributed to surface water resources as derived from the USGS data in year 2005. Figure 2b presents the ratio of total consumptive demand over the total withdrawal demand. The ratio of consumptive over withdrawal demand represents a spatially varying measure of the potential for return flow. We refer to “water reclaiming” as the simulated process in which the return flow proceeds back into the surface water system and can be reused, “recycled” or

Figure 4. Relative change in ability of the integrated water model to meet the water demand when adding groundwater and return flow modules. A decrease in historical supply deficit means an improvement in the ability of the integrated modeling framework to represent realistic water management.

“reclaimed” for downstream withdrawal needs. Water reclaiming potential will be active only to the extent withdrawals can be met. When both the groundwater and return flow modules are active, the withdrawals assigned to the groundwater source of supply are always met. It corresponds to “flow enhancement” as the surface water flow is augmented with the unconsumed groundwater withdrawals which is always met by default.

High consumptive demand over the US is located in regions of intensive irrigation (Midwest, lower Mississippi, Columbia and Snake river valleys over the Pacific Northwest, and Central Valley in California) and in regions of large urban centers (Figure 2c). Consumptive demands are 1/4th of the withdrawal demand on average over the US, 1/1.7th for irrigation and 1/10th for nonirrigation sectors (Figure 2a). The ratio for irrigation is relatively uniform throughout the US, but the ratio for nonirrigation has an east-west pattern with ratios of 1/12th and 1/4.5th over the eastern and western US, respectively. This pattern is related to the large withdrawals for the energy industry in the eastern US due to the widespread application of once-through cooling technology [Liu et al., 2015]. The fraction of water demand assigned to groundwater source is larger in regions with high irrigation demand in the Midwest and the Southeast and locally over the western US. Urban areas are also groundwater dependent in the Midwest and the East Coast. The Upper Colorado and Missouri headwaters have little dependence on groundwater (blue strip in Figure 2b). Those regions should be less affected by the groundwater and return flow modules.

4.2. Spatial Redistribution of Streamflows and Deficits

Both the groundwater and return flow modules can redistribute water in space and consequently influence regional differences in water deficits. We demonstrate and quantify how each individual module contributes to the ability of the water management to meet the IA spatially distributed sectoral water demands (realism of the representation of human activities). More specifically, we focus on identifying how regulated streamflow and water deficit spatial distribution are affected by how the return flow and groundwater modules manage the IA spatially distributed sectoral water demands. The combined effect of the return flow and groundwater module could be twofold: the return flow module changes the availability of local water to provide for withdrawals instead of consumptive demand in grid cells that are too far to be supported by reservoirs and cannot benefit from the reservoir’s supply return flow as additional local supply. The withdrawals used as part of the return flow module can add stress to the surface water system, where the ratio of consumptive demand over withdrawals is small and where reservoir storage is low, i.e., the eastern US (Figures 2a, 2b and equation (4a)). Including the groundwater module allows more of the total demand (both consumptive and withdrawal) to be met so it may lower the relative deficit with respect to the

Figure 5. Benchmark mean annual regulated flow in cubic meter per second. Second row shows the fractional change in regulated flow with respect to the benchmark for experiments using (b) return flow, (c) groundwater, and (d) both. Yellow indicates no change, green to blue indicates increase and orange to red indicates drying.

baseline. Different processes might dominate the spatial redistributions of water resources in different regions. Therefore we evaluate the impacts of groundwater use and return flow by looking at the spatial patterns of various hydrologic aspects simulated in the four different experiments.

Figure 5 presents the regulated flow simulated with the benchmark (WM), and the relative difference (ratio) in regulated flow due to redistribution of water from sectoral water management with return flow of surface water only (WM_return), changes in water storage due to the addition of groundwater as a source of supply (WM_GW), and the combined effects of return flow and groundwater supply (WM_GW_return). An east-west contrast is identified in the hydrologic pattern of the return flow dynamics (Figure 5b). Over the eastern US where the consumptive over withdrawal demand is the lowest, the potential for recycling is high and the regulated flow tends to be either maintained (yellow for unity ratio) or increased (green to blue). As explained next with the pattern on supply deficit (equation (3)), the surface withdrawals cannot always be met (fraction F in equations (2) and (3)) and as such, less consumptive use demand is met and removed from the system, resulting in little recycling (equation (5)) and more water in the streams and grid cells. Because there is little storage over the East, there is little opportunity to store and redistribute the increased flow into downstream grid cells. In reality, prorationing over the western US is based on a priority system with senior and junior water rights even if senior water rights are located downstream of junior water rights (Prior Appropriation). Over the eastern US, the Riparian Rights are applied and allow upstream users to use water on their properties as needed. In our modeling, the allocation from local streams follows the Riparian Rights while the allocation of remaining demand to reservoirs tends to even out the appropriation over all grid cells.

Over the Midwest and western US, the potential for reclaiming is low as the differences between withdrawals and consumptive demands are low. Over the Midwest, large downstream irrigation projects in

a) Benchmark

Daily unmet consumptive water demand per grid cell (cubic meters)

Changes in unmet water demand (consumptive or withdrawals) with respect to the benchmark unmet consumptive demand

b) Return flow

c) Groundwater

d) Groundwater & return flow

Changes in daily unmet water demand per grid cell (cubic meters)

Figure 6. Benchmark mean annual deficit in cubic meter per day. The second row shows the absolute change in supply deficit with respect to the benchmark for experiments using (b) return flow, (c) groundwater, and (d) both. Yellow indicates no change, green to blue indicates decrease in deficit and orange to red indicates increase in deficit.

southern Colorado, southern California and Central Valley, Columbia River Basin Project and Snake River Basin, local water flow tends to become higher with return flow because the higher withdrawals can be met by upstream reservoirs and local streams. The streams are however drier until they reach large capacity reservoirs (Garrison over the Missouri, for example) or the outlet (Colorado, California). Moreover, since the groundwater module allocates water demand to surface and groundwater systems, this results (Figure 5c) in an increase in regulated flow in places where groundwater supply can be used and in the downstream rivers. Over northern Texas, Arkansas Red and lower Missouri, the main river flow enhancement due to groundwater is above 50% locally and it continues down to the river outlet, though with a lower factor. The combined effects of return flow and groundwater source (Figure 5d) induce an increase in the overall flow. Spatial differences are notable where groundwater is the main source of supply and downstream of the region that is fed by the return flow (Figure 5c). Overall, the hydrological pattern from the return flow is more pronounced than the hydrological pattern from the groundwater module.

Figure 6 shows the average daily deficit for the benchmark experiment and the absolute difference in unmet consumptive demand. For experiments WM_return and WM_GW_return, the unmet withdrawal demand was adjusted to reflect the unmet consumptive demand by simply conserving the ratio of met over total demand (equation (3)). So all panels are in units of consumptive demand for proper evaluation. Comparing the return flow experiment with the benchmark (a and b) highlights the east-west pattern shown earlier by the change in regulated flow. Over the East, we note the higher stress from high R_{sfc} values in equation (4), resulting in constrained withdrawals (lower F in equation (2)) and therefore higher flows and increased supply deficit (equation (3), lower F). Over the Midwest and Western US, we see two types of patterns. The first one (yellow to blue or blue only) represents the reclaiming of the return flow in which the supply deficit is either maintained (yellow) or decreased (blue). This is feasible since the demand can be met in the first place due to the large storage capacity on which the grid cells rely on for

Figure 7. Change in relative deficit for regions over the U.S. categorized as East of Mississippi (regions 1–6), Midwest (regions 7–13), and Western U.S., (regions 14–18) as a function of the fraction of consumptive over withdrawal demand. The changes are for management using surface water return flow (return) and combined groundwater and return flow from both surface and groundwater (combined) with respect to management using surface water system only.

water supply. The second pattern is a red-to-blue transition that corresponds to a higher deficit upstream due to higher demands that cannot be met. Also the storage capacity can aggregate the unused water and redistribute it in space to its dependent grid cells and decrease their supply deficit (blue). This spatial redistribution is possible again due to the larger storage capacities. The east-west pattern of the return flow module reflects a combination of the difference between withdrawals and consumptive demands, and storage capacity.

Overall, the use of groundwater as additional sources of supply has a larger effect on the supply deficit than the return flow module. Comparing a and c, the largest effects of groundwater supply are on the spatial pattern of water stress in regions such as the Ogallala aquifer, lower Mississippi, and Central Valley where a significant amount of the demand is met by groundwater and where consumptive over withdrawal demand ratios are relatively high (mostly irrigation). Eastern US urban centers are relieved but only 30% of their demand is met by groundwater, while non irrigation consumptive over withdrawal ratio are very low, resulting in remaining shortage. While the allocation of some of the water demands to groundwater sources and the accounting for return flow coming from the groundwater source reduces deficit over most of the US (comparing b and d Figure 6), some water deficit remains over some of the urban centers in the eastern US because of the limited surface water resource. Overall, in terms of water supply deficit, the groundwater module has the largest impacts, mostly over the western US, while the return flow module has significant impacts across the full domain.

To analyze the underlying drivers of the emerging regional patterns in water supply deficits, we look at how the consumptive over withdrawals water demand ratios and the fraction of demand expected to be met by groundwater affect supply deficits in each of the 18 US water resources regions. The sectoral spatially distributed consumptive over withdrawal ratios and allocation to groundwater system are characteristics of the coupling between IA and ES and to this analysis (supporting information Table S1). Figure 7 presents the regional change in relative supply deficit with respect to the benchmark (WM) simulation. The lower the ratio, the higher the potential for return flow. As explained earlier, a very low ratio brings stress locally and has been shown to reduce the ability of the water system to meet the withdrawal demand over the eastern US (−1% to +24% deficit), western US (−2% to +8%), and Midwest (−1% to +18%). On the contrary, a higher ratio allows the system to meet more demand and mitigate the increase in relative deficit. The representation of groundwater supply (WM_GW_return) reduces the supply deficit across the entire domain compared to the simulation with return flow from surface water system only (WM_return). In particular, the relief over the eastern US mitigates the stress from the withdrawals (WM_return) compared to the benchmark representation. The figure quantifies the east-west contrast due to the return flow module, and quantifies the groundwater contribution to improving the performance of the water management.

Figure 8 shows the change in relative deficit with respect to the benchmark as a function of the regional dependence on groundwater. The figure quantifies the regional improvement in water deficit due to the groundwater module. The western US has decreases in water deficit ranging from −1% to −23% with

Figure 8. Change in relative deficit for regions over the U.S. categorized as East of Mississippi (regions 1–6), Midwest (regions 7–13), and Western U.S., (regions 14–18) as a function of the fraction of the demand assigned to groundwater supply. The changes are for management using groundwater as additional source of supply from groundwater (GW) and combined groundwater and return flow from both surface and groundwater (combined) with respect to management using surface water system only.

groundwater use. The combination with using return flow enhances the decrease in deficit due to the higher reservoir capacities and localized demands in regions that can be supplemented by supply from the reservoirs, as explained earlier (−4% to −33%). The eastern US, with an average 30% of demand to be met by groundwater, shows limited decrease in relative deficit due to groundwater use compared to the baseline (−2% to −11%), and a reduced decrease in relative deficit when using the return flow module in combination with the groundwater module (−5% to +5%). The Midwest, which actually depends on a deep aquifer, shows a more critical dependence on groundwater supply (higher fractions and decrease in relative supply deficit ranging from −10% to under −40%). The figure demonstrates and quantifies the contribution of the groundwater module to the east-west contrast by modulating the performance over the Midwest.

The above findings are original for IA-ES studies as they could not be shown based on terrestrial water storage variations using country-specific sectoral allocation to groundwater and consumptive over withdrawals demand ratios [Döll *et al.*, 2012], or using the finer spatial resolution USGS groundwater allocation but no concurrent and spatially distributed use of consumptive and withdrawal demands across sectors [Pokhrel *et al.*, 2015] (supporting information Table S1).

5. Discussion

We have used an integrated modeling framework with and without groundwater use and return flow individually and in combination. Results have focused on the spatial patterns of changes in regulated flow and supply deficit as a proxy for the representation of water management. Here we summarize the effects of return flow and groundwater use and discuss how they relate to modeling assumption and data availability with respect to previous studies, and future directions.

5.1. Effects of Return Flow

The return flow module is intrinsically linked to the representation of withdrawals and consumptive water demands by sectors. In other ES studies, the use of the return flow module was assumed to be more realistic but due to data availability challenges, the ratio of sectoral consumptive demand over withdrawals is based on country-specific ratio for large-scale studies [Döll *et al.*, 2012]. In this study, we demonstrate the need and quantify the effect of using spatially distributed sectoral consumptive over withdrawals ratio. We also quantify the improvement of using sectoral and spatially distributed consumptive over withdrawal ratio from the perspective of realistic water management representation and toward building integrated modeling frameworks to evaluate adaptation and mitigation strategies. Results from our modeling experiments show that the return flow component associated with the IA spatially distributed sectoral consumptive over withdrawal demand ratios is a major driver for the spatial redistribution of water resources and water deficits in the US, with distinct variations between the eastern and western regions. More specifically, with the return flow component, the transport of water (extraction and return) is enhanced when the difference

between withdrawals and consumptive use increases (nonirrigation sector) and withdrawals can be met. In practice, in regions where withdrawals are very high and the demand cannot be met by reservoirs (usually nonirrigation demand over the eastern US), including return flow results in higher flows and higher supply deficit at the same time in the regions. That is, even though the actual water supply increases, if the withdrawal cannot be met, the overall shortage for consumptive use increases in specific locations, urban centers in particular. This shortage can be overestimated due to the lack of interbasin transfer, desalination, and other local water reuse technologies. In regions where the increased demand due to withdrawals can be met by reservoirs (mostly irrigated and large storage capacity), the regions will have lower supply deficit and localized wetter areas because of the return flow. Moreover, the analysis highlights how the representation of more complex water management (multiple sectors and associated technological efficiency for use and delivery) can also affect the spatial distribution of water fluxes and water deficits. The parameterization of sectoral withdrawals over consumptive use ratios also has implications for further two-way coupling of regional integrated assessment and Earth system models. For example, return flows could affect evapotranspiration estimates, freshwater discharge to the oceans, and land-atmosphere feedbacks.

5.2. Effects of Groundwater Use

The effect of using groundwater, which is associated with the IA spatially distributed sectoral water demands, has a localized effect that corresponds to grid cells with significant allocation of water demand to groundwater source. From a modeling perspective, the representation of groundwater shows the largest impact toward a more realistic representation of human activities. This has been an assumption in many other large-scale studies [Pokhrel *et al.*, 2015; de Graaf *et al.*, 2015; Wada *et al.*, 2014], which we specifically quantify in this paper through the accounting of supply deficit rather than through the evaluation of terrestrial water storage variations. The representation of groundwater ensures that the water management performance is closer to observations as more historical demand is met. In terms of Earth system modeling, it also affects the water balance. The higher the dependence on groundwater, the higher the effects, which include an increase in river flows down to the outlet of the basin and higher local surface water flows. The major assumption in water resources management including reliance on groundwater comes from the fractions of demand attributed to the groundwater and surface water systems. Literature varies on this subject and is evolving from all unmet demand allocated to unsustainable groundwater [Biemans *et al.*, 2011; Döll *et al.*, 2012; Pokhrel *et al.*, 2012] toward a more dynamic distribution between surface and renewable groundwater systems [Pokhrel *et al.*, 2015; de Graaf *et al.*, 2015; Wada *et al.*, 2014]. This paper also demonstrates the influence of using spatially and sectorally varying distribution of the water demand on the water management, which in turn is expected to influence the future two-way coupling of integrated assessment model and Earth system model, groundwater dynamics and evapotranspiration fluxes.

5.3. Spatial and Temporal Scale Dependencies

This study evaluated the effects of return flow and groundwater use on the redistribution of water resources in the US. The analysis is performed on the spatial distribution corresponding roughly to the HUC 2 scale and on annual time scale. Since the impacts of water management are scale dependent, our results are sensitive to the temporal and spatial resolutions of modeling as well as how return flow and groundwater use are represented in the model. For example, relaxing the assumption that unconsumed water is returned to the grid cells where withdrawals are extracted may lead to some differences in how return flow redistributes water resources at subbasin scale. Sensitivity of the impacts of return flow and groundwater use to the methods used to represent them and the scale at which they are applied should be evaluated in future studies.

6. Conclusions

This paper evaluates the implementation of groundwater use and return flow components to represent the impacts of IA based spatially distributed sectoral water demands (withdrawals and consumption) and allocation to surface and groundwater systems on water resources redistribution in an integrated modeling framework consisting of a regional integrated assessment model coupled with a regional Earth system model (IA-ES). The implementation differs from other frameworks by its spatial distribution of sectoral demand to surface and groundwater demands, as well as spatial and sectoral differentiation between withdrawals and consumptive uses, and by allowing water shortage to occur and accounting for it. The

framework was analyzed not only with respect to changes in spatial patterns of surface hydrology due to groundwater use and return flow but also with respect to the ability of the water management system to meet the historical demand and reproduce historical and sectoral water deficits. This is an essential aspect of the integrated IA-ES modeling framework aiming at evaluating mitigation and adaptation strategies in the future.

We show that spatial distribution of sectoral human activities associated with groundwater extractions and water use recycling have pronounced effects on the spatial patterns on streamflows and water deficits. Such effects may induce feedbacks to regional climate and enhance the capacity of Earth system models to better capture the consequences of human water use activities on other Earth system components. Despite the relatively simple representation of groundwater and return flow in this study, the findings can inform future development in linking Earth system models and integrated assessment models. In particular sectoral water management has been shown to add differentiation in water stress because of the lower consumptive over withdrawal demand ratio for nonirrigation activities. The east-west variation in sectoral uses and associated spatial variations in the ratios of consumptive over withdrawal demand, combined with differences in reservoir storage capacity create a clear east-west differentiation in water resources recycling. Our findings emphasize the need for accurate parameterization of the return flow component, specifically linked to the sectoral and spatial variability in consumptive over withdrawal demand ratios, for accurate representation of water recycling in Earth system models and integrated assessment models. The water resources recycling is important for the water and energy balances in the Earth system under current and future land use conditions. Understanding how return flow and groundwater pumping may alter the water budget (e.g., ET, runoff, recharge) would necessitate a two-way coupling (CLM-WM) approach and should be evaluated in future studies.

Our analysis also motivates the need to better represent sectoral water resources management in Earth system models using, for example, two-way coupling with integrated assessment models (WM-GCAM), and including finer temporal scale reservoir operations and rules for redistribution of sectoral supply for IA-ES evaluation of adaptation and mitigation strategies in the future. Further spatiotemporal downscaling approaches for sectoral water demand are also needed, together with dynamic allocation of demand to groundwater and surface systems in integrated assessment models in coordination with Earth system models land cover parameterization and water table levels. The two-way coupling would allow bridging the scales in the representation of water management and combine large-scale evaluation with local effect such as finer scale surface water-groundwater interactions and feedbacks into the atmosphere.

Acknowledgments

We wish to thank the editor and anonymous reviewers for their help in improving earlier versions of this manuscript. All data and model code used in this paper are available upon request. The integrated modeling framework is part of the Platform for Regional Integrated Modeling and Analysis (PRIMA) initiative at the Pacific Northwest National Laboratory. This work is also partly supported by the U.S. Department of Energy, Office of Science, Biological and Environmental Research (BER) as part of the Accelerated Climate Modeling for Energy (ACME) project funded by the Earth System Modeling program. This work is also partly supported by the Office of Science of the U.S. Department of Energy through the Integrated Assessment Research Program. The Pacific Northwest National Laboratory is operated for DOE by Battelle Memorial Institute under contract DE-AC05-76RL01830.

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