ENVIRONMENTAL STUDIES

Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion

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Groundwater pumping has caused marked aquifer storage declines over the past century. In addition to threatening the viability of groundwater-dependent economic activities, storage losses reshape the hydrologic landscape, shifting groundwater surface water exchanges and surface water availability. A more comprehensive understanding of modern groundwater-depleted systems is needed as we strive for improved simulations and more efficient water resources management. Here, we begin to address this gap by evaluating the impact of 100 years of groundwater declines across the continental United States on simulated watershed behavior. Subsurface storage losses reverberate throughout hydrologic systems, decreasing streamflow and evapotranspiration. Evapotranspiration declines are focused in water-limited periods and shallow groundwater regions. Streamflow losses are widespread and intensify along drainage networks, often occurring far from the point of groundwater abstraction. Our integrated approach illustrates the sensitivity of land surface simulations to groundwater storage levels and a path toward evaluating these connections in large-scale models.

INTRODUCTION

Human development has markedly altered hydrologic systems across the globe. Storing and diverting large volumes of water to support human use and crop production redistributes water spatially, changes streamflow timing, and decreases overall water availability. Recent global studies highlight the extent of human intervention in hydrologic systems and demonstrate large water demand with the expansion of irrigated agriculture (*1*), as well as hydrologic disconnection caused by river impoundments (*2*) and cascading water scarcity with human activities (*3*). Despite local and global efforts to quantify human diversions, many interdependencies between anthropogenic water use and natural hydrologic processes remain poorly quantified. Uncertainty in these connections limits our ability to sustainably manage water resources.

Groundwater is a critical supply for human systems. It supports more than 40% of irrigation globally (*4*) and is the sole water source for crops in many arid regions that could not otherwise support agriculture. When used in conjunction with surface water, it can stabilize total water supply. Unfortunately, the reliability of groundwater, and its relative abundance in otherwise water-limited locations, has also lead to its overuse. Sustained groundwater pumping has resulted in sustained groundwater storage losses globally (*5*, *6*). In the United States alone, roughly 800 km^3 of water was depleted from groundwater storage over the 20th century (*7*). Unlike surface water reservoirs and streamflow, which are routinely subject to large interannual fluctuations, groundwater storage losses have generally been increasing over time. While multiple studies have evaluated the ability of remaining groundwater supplies to sustain future human demands, outside of several heavily studies regions, much less is known about the impacts of widespread storage losses on watershed function, and global models generally do not include these losses in their simulations.

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Groundwater pumping is not an isolated activity; in managed agricultural systems, pumping generally supports irrigation. Connections between irrigation, recharge, soil moisture, atmospheric water content, and downwind precipitation have been demonstrated [e.g., (*8*–*10*)]. However, the impact of storage changes has not been previously isolated from other water management operations (e.g., irrigation and surface water diversions) at the continental scale. Groundwater storage changes are different from many other management impacts because the effects of storage losses are spatially diffuse and temporally persistent; pumping impacts can be observed outside of areas where groundwater irrigation is directly applied and will persist even if irrigation practices change and pumping is curtailed. The long-term storage losses caused by a century of groundwater development can be viewed as a large-scale reshaping of the integrated hydrologic landscape. This will influence watershed response to both natural and human perturbations moving forward. This study seeks to isolate the impact of decreased groundwater storage on the hydrologic landscape and start to unravel the hydrologic differences between modern depleted groundwater systems and natural watersheds.

Groundwater surface water exchanges play an important role in the dynamics of natural hydrologic systems, and there is an increasing push to include groundwater processes in global-scale land surface and climate models. In an idealized sense, groundwater can be conceptualized as a subdued replica of topography, with recharge occurring across the landscape and lateral flow in the subsurface creating convergence zones at low elevations [e.g., (*11*)] (Fig. 1A). Where the water table is deep (often at high elevations), surface water generally recharges down to the water table; however, when groundwater is within a critical depth range (less than about 10 m from the land surface), connections between water table depth and soil moisture can help support evapotranspiration (ET) (*12*–*14*). In addition, water can move laterally through the subsurface, from the point of recharge eventually converging to surface water bodies where it can discharge to streams as baseflow [e.g., (*15*, *16*)]. The relatively slow processes of infiltration and lateral redistribution via groundwater flow result in groundwater levels, and groundwater