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Climate variability and vadose zone controls on damping of transient recharge

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ABSTRACT

Increasing demand on groundwater resources motivates understanding of the controls on recharge dynamics so model predictions under current and future climate may improve. Here we address questions about the nonlinear behavior of flux variability in the vadose zone that may explain previously reported teleconnections between global-scale climate variability and fluctuations in groundwater levels. We use hundreds of HYDRUS-1D simulations in a sensitivity analysis approach to evaluate the damping depth of transient recharge over a range of periodic boundary conditions and vadose zone geometries and hydraulic parameters that are representative of aquifer systems of the conterminous United States (U.S). Although the models were parameterized based on U.S. aquifers, findings from this study are applicable elsewhere that have mean recharge rates between 3.65 and 730 mm yr^{-1}. We find that mean infiltration flux, period of time varying infiltration, and hydraulic conductivity are statistically significant predictors of damping depth. The resulting framework explains why some periodic infiltration fluxes associated with climate variability dampen with depth in the vadose zone, resulting in steady-state recharge, while other periodic surface fluxes do not dampen with depth, resulting in transient recharge. We find that transient recharge in response to the climate variability patterns could be detected at the depths of water levels in most U.S. aquifers. Our findings indicate that the damping behavior of transient infiltration fluxes is linear across soil layers for a range of texture combinations. The implications are that relatively simple, homogeneous models of the vadose zone may provide reasonable estimates of the damping depth of climate-varying transient recharge in some complex, layered vadose zone profiles.

1. Introduction

A growing number of studies report that groundwater levels can fluctuate in response to low frequency and persistent global-scale climate patterns that have quasi-periodic oscillations on interannual to multidecadal timescales (e.g., Fleming and Quilty, 2006; Holman et al., 2009; Perez-Valdivia et al., 2012; Tremblay et al., 2011; Venencio and García, 2011), which affect infiltration and recharge. Complicating the interpretation of these teleconnections is that groundwater levels also respond to groundwater pumping trends and variability largely on seasonal timescales (Gurdak, 2017). This so-called *climate-induced pumping* has been detected on timescales ranging from less than one year (Russo and Lall, 2017) to scales consistent with the El Niño/Southern Oscillation (ENSO) (Gurdak et al., 2007). These physical mechanisms have largely been inferred from statistical and spectral analysis of hydroclimatic time series (e.g., Gurdak et al., 2007; Hanson et al., 2006, 2004; Holman et al., 2011; Kuss and Gurdak, 2014; Russo and Lall, 2017). However, teleconnections that have not been evaluated by mechanistic models may be limited for understanding and predicting groundwater responses to future climate.

Increasing demands on groundwater resources from the Water-Energy-Food Nexus (Taniguchi et al., 2017) and climate variability and change (Green et al., 2011; Taylor et al., 2012) continues to raise the importance of understanding and accurately predicting current and future recharge (Meixner et al., 2016). These predictions can be improved through a better understanding of the properties of the vadose zone that control a time-varying recharge response to climate variability (Hunt et al., 2008). Such controls are poorly understood because of the nonlinear relations among unsaturated flow, pressure, water content, and hydraulic diffusivity in

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the vadose zone (Dickinson et al., 2014). These challenges are further compounded by a general lack of long-term field observations of such variables from the vadose zone that are necessary to detect time-varying recharge in response to climate variability on interannual to multidecadal timescales (Gurdak et al., 2007); although recent studies have begun monitoring the vadose zone under different climate regimes and land use (e.g., Baram et al., 2012; Carrera-Hernandez et al., 2011; Strobach et al., 2014; Turkeltaub et al., 2014).

As noted by Dickinson et al. (2014), the nonlinear complexity of controls on transient recharge has often limited the direct representation of recharge in groundwater models and resource assessments, which in many cases have assumed a long-term, steady-state recharge flux. Under some conditions, assigning a slowly varying or constant recharge flux in a groundwater model is justified because periodic or episodic variations in surface infiltration fluxes smooth out or dampens with depth prior to recharge (Dickinson et al., 2014). However, recent physically-based modeling studies (Dickinson et al., 2014; Velasco et al., 2015) and the previously mentioned studies that use time-series and spectral analysis have identified some conditions where climate variability results in transient recharge fluxes that are not dampened within the vadose zone. An improved ability to model recharge is relevant for improving prediction of groundwater response to future climate and the associated global-to-local scale management decisions and policy regarding sustainable groundwater (Famiglietti, 2014). This is particularly needed for aquifers in semi-arid and arid climates that often are in overdraft conditions, have relatively thick vadose zones, and are generally predicted to have less recharge and (or) more episodic recharge events under future climate change (Green et al., 2011; Taylor et al., 2012; Treidel et al., 2012). To address this need requires a review of the state of understanding of coupled climate variability and vadose zone dynamics.

1.1. Climate variability

The expected trends in many hydrologic processes, including recharge rates and mechanisms due to human-induced climate change, particularly over the first-half of the 21st century, can only be fully appreciated when combined with understanding of the overprinted global-scale climate variability. The majority of climate change impact studies on recharge have largely focused on human-induced climate change, often using the approach of coupling downscaled climate data from global circulation models (GCMs) that drive hydrologic models to estimate recharge rates and mechanisms under future climate change, commonly by the middle to end of the 21st century (Green et al., 2011; Meixner et al., 2016; Taylor et al., 2012; Treidel et al., 2012). The current generation of GCMs project that mean climate across many regions of the globe will move to a state continuously beyond historical variability by the mid-21st century (Mora et al., 2013), which will likely alter the frequency, magnitude, and other spatiotemporal characteristics of climate variability patterns (Stoner et al., 2009). However, the comparatively short-term planning horizon (often years to decades) for most groundwater resource management decisions means that transient recharge in response to climate variability on interannual to multidecadal timescales has immediate and tangible implications for groundwater sustainability (Gurdak et al., 2009).

Climate variability occurs on all temporal scales that extend beyond weather events, and is defined as the difference between current climate conditions and the mean state over a larger temporal scale (Ghil, 2002). Climate variability is often characterized using indices that combine sea surface temperatures, sea level pressures, geo-potential heights, and wind speed, among other atmosphere–ocean variables (Ghil, 2002). The indices that represent the six leading atmospheric-ocean circulation systems that affect North American interannual to multidecadal climate variability include the Atlantic teleconnection patterns: the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and Atlantic Multidecadal Oscillation (AMO); and the Pacific teleconnection patterns: ENSO, Pacific Decadal Oscillation (PDO), and Pacific-North American Oscillation (PNA). The most widely accepted quasi-periodic cycles for these systems range from <1–70 years, including 6–12 months (AO), 3–6 years (NAO), 50–70 years (AMO), 2–7 years (ENSO), 15–30 years (PDO), to <1–4 years (PNA) (Enfield et al., 2001; Ghil, 2002; Hurrell, 1995; Kuss and Gurdak, 2014; Mantua and Hare, 2002; NOAA, 2015; Stoner et al., 2009; Wolter and Timlin, 2011). While GCMs vary in their ability to represent these cycles skillfully, recent analysis demonstrate some robust projections for how they may evolve through the 21st century, such as changing in amplitude, time scale, and increasing the meteorological extremes with which they are associated (Chen et al., 2017; Zhang and Delworth, 2016).

The Atlantic and Pacific teleconnections influence the spatiotemporal patterns of precipitation, air temperature, drought, snowpack and melt, evapotranspiration, stream discharge, and other land-surface hydrologic processes across the continental U. S, North America, and other regions (Bayari and Yildiz, 2012; Beebee and Manga, 2004; Brabets and Walvoord, 2009; Cayan et al., 1999; Enfield et al., 2001; Kondrashov et al., 2005; Maheu et al., 2003; Mantua et al., 1997; Mazouz et al., 2012; McCabe et al., 2004; Ropelewski and Halpert, 1986; Sabziparvar et al., 2011; Tremblay et al., 2011; Vicente-Serrano et al., 2011). Such variability in surface hydroclimatology is expected to influence time-varying infiltration, downward water flux in the vadose zone, and ultimately recharge rates and mechanism (Gurdak et al., 2007; Hanson et al., 2004; Kuss and Gurdak, 2014). However, the teleconnections patterns that exist in surface hydrologic processes are not necessarily the same as those preserved in the subsurface processes that affect groundwater levels (Velasco et al., 2015). Much of the subsurface hydrologic response is also a function of the hydraulic properties of the vadose zone (Dickinson et al., 2014).

1.2. Vadose zone hydraulic properties and climate-varying recharge

Recent research has begun to consider the properties of the vadose zone that may influence whether groundwater levels may respond to climate variability. To investigate the role of the vadose zone, these studies have focused on the relations between soil and water properties and periodic flow in the vadose zone that could be driven by climate variability (Bakker and Nieber, 2009; Dickinson et al., 2004, 2014; Pool and Dickinson, 2007). These relations become important when climatic forcings at the land surface can be damped in the vadose zone prior to reaching the water table (Velasco et al., 2015). Bakker and Nieber (2009) derived an analytical solution to the Richards equation for vertical, one-dimensional transient flow that was used to predict the movement of cyclical, sinusoidally-varying fluxes at the land surface where the infiltration can be assumed to be a function of precipitation and evaporation. Bakker and Nieber (2009) found that flux variations damp with depth in the vadose zone such that beyond a certain depth (referred as the damping depth (d)), the flux could be approximated as steady (Bakker and Nieber, 2009).

Expanding on the work of Bakker and Nieber (2009), Dickinson et al. (2014) developed a screening tool for evaluating how variability of a cyclical infiltration pattern at the land surface was damped with depth in the vadose zone. If the flow variability damped to within 5% of the original amplitude, they stated that the assigned recharge in numerical groundwater flow models can be assumed to be steady. However, if >5% of the infiltration variability remained at the depth of the water table, recharge is