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GRACE Groundwater Drought Index: Evaluation of California Central Valley groundwater drought

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ABSTRACT

Quantitative approaches to assess the complexity of groundwater drought are hindered by the lack of direct observations of groundwater over space and time. Here, we present an approach to evaluate groundwater drought occurrence based on observations from NASA's Gravity Recovery and Climate Experiment (GRACE) satellite mission. Normalized GRACE-derived groundwater storage deviations are shown to quantify groundwater storage deficits during the GRACE record, which we define as the GRACE Groundwater Drought Index (GGDI). As a case study, GGDI is applied over the Central Valley of California, a regional aquifer undergoing intensive human activities and subject to significant drought periods during the GRACE record. Relations between GGDI and other hydrological drought indices highlight our ability to capture drought delays unique to groundwater drought. Further, GGDI captures characteristics of groundwater drought that occur as a result of complex human activities and natural changes, thus presenting a framework to assess multi-driver groundwater drought characteristics.

1. Introduction and background

By the end of 2015, the prolonged and well-documented drought in California, recognized as starting in 2012 (Griffin and Anchukaitis, 2014), had reached historically unprecedented conditions. The Palmer Drought Stress Index (PDSI) (Palmer, 1965), a commonly used index to evaluate drought based on a simple water budget model (Alley, 1984), identified June and July of 2014 as having the two lowest indices in the Central Valley of California, where records date from 1900 to present, while the spring of 2015 exhibited PDSI values in the lowest 95% quantile (Fig. S1). Equally severe deficits were documented in the Standardized Precipitation Index (McKee et al., 1993) (Fig. S1). A comparison between drought indices and streamflow reconstruction further illustrates the historic nature of the drought, which potentially represents the worst California drought in the last 1200 years (Griffin and Anchukaitis, 2014). The prolonged drought, attributed to a persistent upper level weather dipole (Wang et al., 2014), resulted in a cascade of impacts affecting rangelands (Larsen et al., 2014), forests (Baguskas et al., 2014; Asner et al., 2016), agriculture and socioeconomics (Howitt et al., 2014) and groundwater (Faunt et al., 2015).

The term drought, used ambiguously above, refers to prolonged dryness manifesting itself in various water deficits including meteorological (precipitation), hydrological (streamflow), agricultural (soil moisture), socioeconomic and groundwater (Dracup et al., 1980; Mishra and Singh, 2010). Drought is largely driven by a change in climatic forcing, for example decreases in precipitation, which develop slowly and can last months to years (Tallaksen and van Lanen, 2004; Tallaksen et al., 2009). The lack of a formal definition of drought (Wilhite et al., 2007) combined with the difficulty in investigating its precursors have resulted in compartmentalized drought indices (for example, hydrological drought: PDSI; meteorological drought: SPI; groundwater drought: SGI (Bloomfield and Marchant, 2013)). Recent studies have sought to evaluate integrated drought indices (Hao and AghaKouchak, 2014; Hao et al., 2014; Ma et al., 2014). Thomas et al. (2014) developed a framework to evaluate a holistic drought characterization using data from the Gravity Recovery and Climate Experiment (GRACE) satellites, focusing on the total water storage deficits to characterize drought occurrence.

As the effect of drought cascades from meteorological to hydrological to agricultural drought, groundwater storage may be impacted

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(Eltahir and Yeh, 1999). Groundwater drought is a distinctive class of drought resulting from the decrease in groundwater recharge (Goodarzi et al., 2016) and the decrease in groundwater storage and discharge (Mishra and Singh, 2010; Bloomfield and Marchant, 2013; Bloomfield et al., 2015). The direct and indirect consequences of anthropogenic influences can be readily linked to exacerbating groundwater drought (Tallaksen and Van Lanen, 2004). During hydrological and agricultural drought periods, water demands are often satisfied by groundwater withdrawals since groundwater storage provides resiliency (Hughes et al., 2012). Excessive groundwater withdrawals can thus magnify perceived drought (Famiglietti et al., 2011; Famiglietti and Rodell, 2013; Castle et al., 2014). Understanding groundwater drought is important in regions where subsurface storage influences regional security (Famiglietti, 2014) given the persistence in groundwater drought (Peters et al., 2003; Hughes et al., 2012). Identifying groundwater drought is important, especially in arid regions where the interplay between groundwater recharge and abstraction results in variable groundwater stress conditions (Richey et al., 2015a). Our ability to identify groundwater drought, however, is hindered by our inability to directly observe changes in groundwater storage.

In California's Central Valley (Fig. 1), it has long been recognized that an overreliance on groundwater to meet water demands has resulted in substantial decreases of groundwater storage (Famiglietti et al., 2011; Scanlon et al., 2012a, 2012b) and subsequent land subsidence (Poland et al., 1975; Faunt et al., 2015; Sneed and Brandt, 2015). In the recent drought, decreases in groundwater storage intensified (Wang et al., 2016) resulting in unprecedented land surface deformation (Farr et al., 2015). As the occurrence of more severe and longer duration droughts are predicted to increase as a result of climate change (Cayan et al., 2006; Cook et al., 2015), our ability to observe hydrologic information to investigate the prevailing characteristics of drought become vital, especially in regards to water resources management (Aghakouchak et al., 2014). In particular, characterizing groundwater storage at the onset of groundwater drought conditions is difficult due to the lack of continuous and spatially representative groundwater observations and the potential temporal offset between various observable drought conditions (i.e. precipitation and soil moisture) and groundwater drought (Calow et al., 1997; Changnon, 1987).

Satellite remote sensing has been established as a powerful tool to observe water storage dynamics at large scales (Rodell and Famiglietti, 1999; Wahr et al., 2006) with the launch of the GRACE satellites. Observations from GRACE gravity anomalies may be converted into changes of water equivalent height thus tracking changes in total water storage across the globe. Previous applications of GRACE have isolated groundwater storage changes (Rodell et al., 2009; Famiglietti et al., 2011; Scanlon et al., 2012a, 2012b; Castle et al., 2014; Scanlon et al., 2015) given auxiliary data to remove other components of the water budget to draw important understanding of regional groundwater storage changes during the GRACE record. Whereas previous studies evaluated GRACE-derived groundwater storage changes as a response to drought (Famiglietti et al., 2011; Scanlon et al., 2012a, 2012b), this study explicitly introduces and evaluates a groundwater drought index based on GRACE observations in an effort to understand and identify groundwater drought. A case study focused on the Central Valley of California is described given the documented episodes of drought in the region (Famiglietti et al., 2011; Cook et al., 2015; Wang et al., 2014).

The development of groundwater drought indicators has employed water budget approaches (Mendicino et al., 2008), statistical applications using in situ groundwater observations (Bloomfield and Marchant, 2013) or hydrologic model simulations (Houborg et al., 2012; Li and Rodell, 2015). In this paper, the water budget approach to derive a groundwater drought index is explored. Given drought propagation through various components of the hydrologic budget (Changnon, 1987; Eltahir and Yeh, 1999; Peters et al., 2003; Peters et al., 2005), we hypothesize that the observable expression of groundwater drought would occur some time after drought is expressed in soil moisture and precipitation indices. Previous groundwater drought

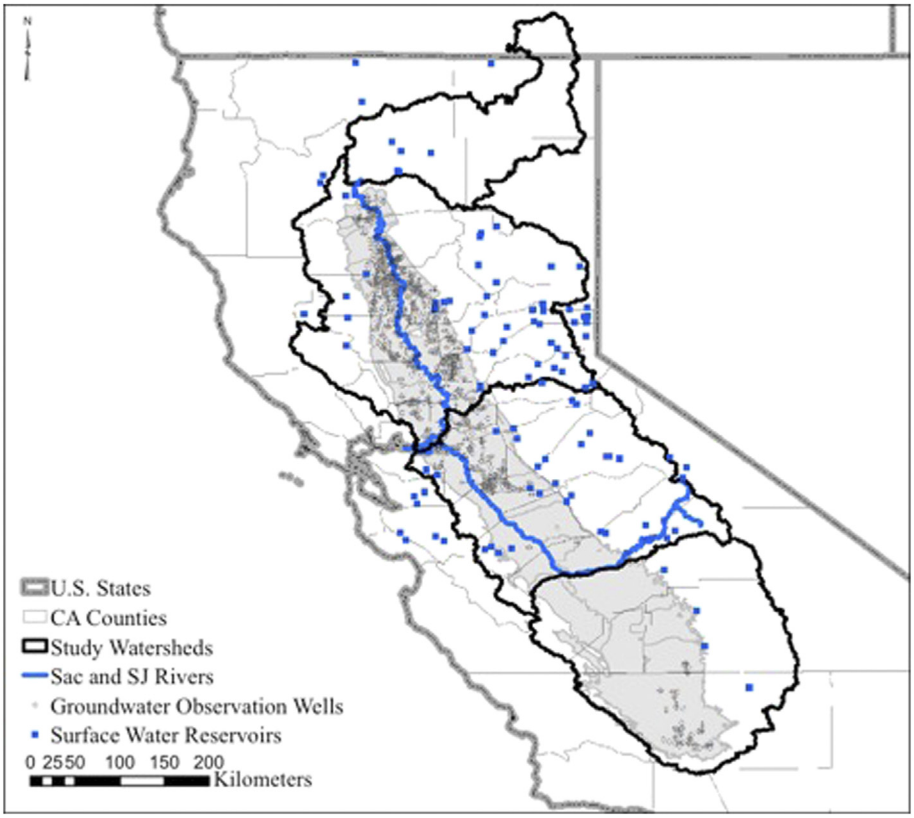

Fig. 1. Site map illustrating groundwater observation wells, reservoirs and the GRACE region used for the study.