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Groundwater variability across temporal and spatial scales in the central and northeastern U.S.

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SUMMARY

Depth-to-water measurements from 181 monitoring wells in unconfined or semi-confined aquifers in nine regions of the central and northeastern U.S. were analyzed. Groundwater storage exhibited strong seasonal variations in all regions, with peaks in spring and lows in autumn, and its interannual variability was nearly unbounded, such that the impacts of droughts, floods, and excessive pumping could persist for many years. We found that the spatial variability of groundwater storage anomalies (deviations from the long term mean) increases as a power function of extent scale (square root of area). That relationship, which is linear on a log–log graph, is common to other hydrological variables but had never before been shown with groundwater data. We describe how the derived power function can be used to determine the number of wells needed to estimate regional mean groundwater storage anomalies with a desired level of accuracy, or to assess uncertainty in regional mean estimates from a set number of observations. We found that the spatial variability of groundwater storage anomalies within a region often increases with the absolute value of the regional mean anomaly, the opposite of the relationship between soil moisture spatial variability and mean. Recharge (drainage from the lowest model soil layer) simulated by the Variable Infiltration Capacity (VIC) model was compatible with observed monthly groundwater storage anomalies and month-to-month changes in groundwater storage.

1. Introduction

Aquifers are a vital source of fresh water. The United Nations estimates that about 2.5 billion people rely exclusively on groundwater for drinking water (http://unesdoc.unesco.org/images/0022/002207/220723E.pdf), and aquifers also provide 43% of the water used for crop irrigation worldwide (Siebert et al., 2010). Recent studies have shown that withdrawals, mostly related to irrigation, in the last several decades have led to significant declines of groundwater in many regions (Rodell et al., 2009; Wada et al., 2010; Famiglietti et al., 2011; Feng et al., 2013; Voss et al., 2013). Such declines, if not reversed, would lead to local and later regional dewatering of aquifers, which would have severe consequences for agricultural productivity and human health. Further, ecosystems may be permanently altered by reduced baseflow to streams and wetlands (Stromberg et al., 1996). Climate change is likely to exacerbate the situation in areas where precipitation rates, timing, and fraction as snowfall shift, while demands on water resources are likely to increase in a warmer environment (Green et al., 2011; Taylor et al., 2012). Improving observation and understanding of groundwater storage and its natural variability is essential if we are to preserve and better manage this precious resource in the future (Famiglietti and Rodell, 2013).

Groundwater varies slowly relative to soil moisture, surface water, and non-permanent snow cover, but it is dynamic on seasonal to interannual timescales (Rodell and Famiglietti, 2001; Alley et al., 2002; Weider and Boutt, 2010). Indeed, variations in terrestrial water storage, particularly groundwater storage, contribute to observed interannual and long term sea level changes (Konikow, 2011; Boening et al., 2012). Studies have shown that seasonal variations of shallow groundwater are strongly influenced by climatologic variables including precipitation and evapotranspiration (Eltahir and Yeh, 1999). Groundwater storage responds to atmospheric conditions integrated over weeks to years, and its

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variability is known to be correlated with climate signals such as the El Nino Southern Oscillation (ENSO) in certain regions (Barco et al., 2010; Perez-Valdivia et al., 2012). As a slow varying component of the water cycle, groundwater has long "memory" and can influence the long-term trends and inter-annual variability of runoff and evapotranspiration (Istanbulluoglu et al., 2012; Wang, 2012). Accurately representing its multi-scale variability in hydrological and climate prediction models is challenging, due in part to limited knowledge of how groundwater variability scales spatially and temporally. Improved understanding of the scales of groundwater variability would benefit the development of such models.

Depending on the application, groundwater monitoring network design may benefit from knowledge of spatial variability which determines the number of wells required to quantify the regional mean groundwater storage condition at a given time. Studies on soil moisture have revealed that its spatial variability increases as a power function of extent (Famiglietti et al., 2008; Brocca et al., 2012; Li and Rodell, 2013), thus providing a mathematical form to relate spatial variability to spatial scale. No such study has been conducted for groundwater. Further, knowledge of groundwater scaling relationships would help to bridge gaps not only between field observations, but also between point and remote-sensing measurements. For instance, terrestrial water storage anomalies obtained from the Gravity Recovery and Climate Experiment (GRACE) mission have shown great promises for estimating groundwater storage changes in various regions (Yeh et al., 2006; Rodell et al., 2007, 2009; Zaitchik et al., 2008; Famiglietti et al., 2011; Voss et al., 2013) but the application of GRACE is also limited by its low spatial resolution, which is about 150,000 km^2 at mid-latitudes (Rowlands et al., 2005; Swenson and Wahr, 2006). Hence there is a significant need for information that would help to interpolate between sparsely distributed well observations and GRACE based groundwater storage change estimates.

We examined the temporal and spatial variability of groundwater storage in nine regions of the U.S. based on monitoring well data archived by the USGS and the Illinois State Water Survey. In this study, "scale-dependency" refers to the dependency of spatial variability on extent, which is one of the scale triplet defined by Western and Blösch (1999) and indicates the dimension length covering all measurements. In addition to in situ data, North America Land Data Assimilation System (NLDAS-2, Xia et al., 2012a) precipitation forcing data and simulated groundwater recharge from the NLDAS-embedded VIC land surface model were analyzed. These were used to investigate the interaction between groundwater and atmospheric forcing and to corroborate inferred groundwater behaviors.

2. Data and methods

Fig. 1 shows the locations of observation wells in Long Island (New York), New Jersey, Massachusetts, Pennsylvania and four sub-basins of the Mississippi River basin: the Upper Mississippi, Ohio-Tennessee, combined Red River and Lower Mississippi (hereafter referred to as "Red-LM"), and Missouri basins. The area and the number of wells within the boundary of each region are provided in Table 1. This data set has been previously used, in part or in whole, for validating GRACE derived or model estimated groundwater storage anomalies (Rodell et al., 2007; Zaitchik et al., 2008; Li and Rodell, 2015). The wells were culled from a much larger archive through examination of the data and available metadata. Each well was determined to be open to an unconfined or semi-confined aquifer and representative of the local water table, i.e., exhibiting minimal direct effects of pumping or injections. Records from many locations were discarded due to brevity or large data gaps.

The majority of the data records were obtained from the USGS Groundwater Watch website (http://groundwaterwatch.usgs.gov/) and the rest from the larger USGS National Water Information System and the Illinois State Water Survey. Most of the sites logged one measurement per month; when multiple measurements were available per month, an average monthly value was used. The lengths of the regional data records range from 10 to over 30 years (Table 1) which is sufficiently long to study the seasonality of groundwater. The wells in Long Island, New Jersey, and Massachusetts are generally located in shallow sandy aquifers formed during the last glacial maximum. Most wells in Pennsylvania are located in fractured rock formations that are likely semi-confined. Wells in the Mississippi basin are installed in a diverse range of aquifer types, and their depths vary significantly. The region-averaged well depth ranges from 9 m below the surface in Massachusetts to 86 m in Red-LM, and the average depth to water varies from 4 m to 17 m (Table 1).

Because this study was only concerned with the variability of groundwater storage anomalies (departures from the long term mean) and not absolute quantity, we set the mean depth to water at each well to zero by subtracting the time series-mean from each measurement. Specific yield (S_y) estimates are needed to convert depth-to-water levels to water storage anomalies as equivalent heights of water, but S_y was not provided in the metadata. The S_y values (see Table 1 for regional averages) were determined individually for each well based on published studies on the aquifer formation or, as a last resort, published S_y estimates for the aquifer type. When multiple possible S_y values were found for a given well, a S_y within that range was selected based on the well depth and comparison of the dynamic range of water depths with those of neighboring wells. For each well, groundwater storage anomalies relative to the series mean were computed by multiplying the monthly depth-to-water measurements (mean removed) by the specific yield, and then taking the additive inverse (negative) of each value (because storage increases as depth-to-water decreases).

NLDAS-2 (Xia et al., 2012a) precipitation forcing data are based on daily precipitation measurements from over 10,000 gauges which are temporally disaggregated using Doppler radar images and spatially interpolated to a 0.125° grid that encompasses the conterminous U.S. and parts of Mexico and Canada (Cosgrove et al., 2003). NLDAS forcing spans 1979 to present and thus covers the entire period of our groundwater dataset.

Due to lack of recharge observations, drainage from the bottom of the lowest soil layer simulated by the Variable Infiltration Capacity (VIC) land surface model, driven by NLDAS, was used as an approximation of groundwater recharge. This drainage variable is often named "baseflow" or "subsurface runoff" in land surface models, which are misnomers that imply the water somehow circumvents aquifer storage and immediately enters the stream system. To avoid confusion, we eschew the model terminology and instead use the terms "drainage" and "recharge" through the rest of the text. VIC (Liang et al., 1994) simulates water and energy states (e.g., soil moisture and temperature) and fluxes (e.g., evapotranspiration and runoff) based on physical equations of the relevant processes on and within the land surface, using atmospheric forcing data (e.g., precipitation and solar radiation) to drive the model forward in time. The evolution of soil moisture is simulated in three soil layers, with 10 cm for the top layer and spatially varying depths for the lower two layers which may reach a total depth of 2.5 m at some locations. Drainage is derived using an empirical function that depends on the wetness of the lowest soil layer and a shape parameter. VIC has been applied in a wide range of hydrological basins for modeling streamflow and other land surface processes (see Xia et al., 2012a). Within NLDAS-2 settings (forcing and spatial resolution), Xia et al. (2012b) showed that VIC produced