AGU PUBLICATIONS

Water Resources Research

COMMENT

10.1002/2015WR018085

This article is a comment on *Richey et al.* [2015], doi:10.1002/2015WR017349.

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Citation:
Sahoo, S., T. Russo, and U. Lall (2016), Comment on "Quantifying renewable groundwater stress with GRACE" by Alexandra S. Richey et al., *Water Resour. Res.*, *52*, 4184–4187, doi:10.1002/2015WR018085.

Received 8 SEP 2015
Accepted 5 MAR 2016
Accepted article online 12 MAR 2016
Published online 7 MAY 2016

Comment on "Quantifying renewable groundwater stress with GRACE" by Alexandra S. Richey et al.

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Richey et al. [2015a] estimate groundwater stress for 37 of the world's largest aquifer systems. Their results suggest a positive annual linear trend in groundwater storage in the Ogallala/High Plains Aquifer, USA (herein referred to as High Plains) using NASA's GRACE satellite data, while previous studies and our analysis using groundwater level observations over the same time period show groundwater depletion. This comment is limited to results from the High Plains, but raises questions about how best to interpret GRACE-derived results for major aquifers globally.

Instruments such as GRACE are revolutionizing our ability to understand changes in the global water balance. A series of publications using GRACE in the past decade have highlighted the ability to map changes in regional groundwater or in total terrestrial water storage. GRACE measurements have been used to estimate water storage changes in regions with scarce ground measurements or where the data are not publicly released by the collecting agencies. It is therefore necessary to assess the accuracy of GRACE-derived estimates in locations where effective ground based data are available.

The recent publications by *Richey et al*. [2015a, 2015b] use GRACE data to show a near-zero, though slight net increase in groundwater storage anomaly from 2003 to 2013 in the High Plains aquifer of 0.16 $\pm$ 0.46 km^3/yr. The sign of the trend was unknown within the margin of error, though it was presented as a positive storage trend, and attributed to spatial averaging across regions of increasing storage in the north and decreasing storage in the south [*Richey et al*., 2015b]. These results contradict previous studies which have estimated groundwater storage depletion averaged over the High Plains aquifer, and our own calculation of storage change and annual storage trend using spatial averaging of groundwater level observations. The presentation of this new estimate would benefit from additional explanation of the disparity from previous estimates, and from a discussion of how best to interpret the results given the size of the errors.

We estimated changes in groundwater storage in the High Plains over the same study time period, 2003–2013, using published annual groundwater level data [*USGS*, 2015]. We performed three analyses using groundwater level observations: (1) calculation of net groundwater storage change between winter 2003 and 2013, using well data interpolated to 500 m $\times$ 500 m, and (2) calculation of annual groundwater storage anomaly trend using monthly data between 2003 and 2013 interpolated to 0.5 $\times$ 0.5°, similar to the method used in the *Richey et al*. [2015a] study, and (3) calculation of groundwater storage anomaly trend using winter averaged data interpolated to 0.5 $\times$ 0.5°. We note that the trend of the storage anomaly and the trend of the estimated storage values should be equivalent.

We used a total of 4953 wells with groundwater level (depth to groundwater) observations in the winter of both 2003 and 2013, for 51,976 wells with observations at some point during the study period. For all analyses, depth to groundwater data were converted to elevation and interpolated using an inverse distance weighing (IDW) method to generate contour surfaces. The two surfaces from winter 2003 and 2013 were differenced to generate an interpolated map of groundwater level change (Figure 1a). Specific yield values for the High Plains aquifer were acquired at 500 $\times$ 500 m^2 resolution [*Cederstrand and Becker*, 1998] (Figure 1b). Groundwater elevation change was multiplied by specific yield to calculate change in groundwater storage (Figure 1c). Errors between actual water level measurements and IDW results were propagated through the differencing step and then bootstrapped (n = 10,000). The mean error was used for the entire aquifer to calculate the groundwater storage change error.

Shallow wells (screen depth $<$ 30 m; n = 1373) were excluded from the results presented here. Both shallow and deep wells (screen depth $>$ 30 m; n = 3580) were reasonably well distributed across the aquifer system,

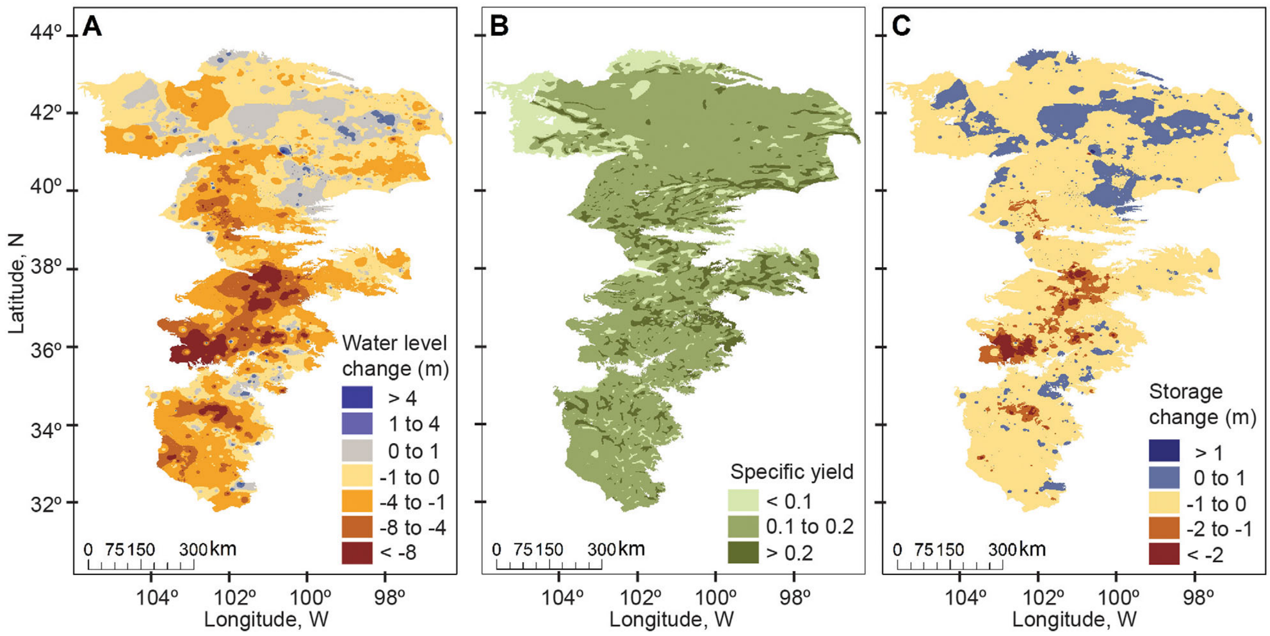

Figure 1. (a) Groundwater level change (m), (b) specific yield, (c) groundwater storage change between 2003 and 2013 (m).

and most major production wells are installed below 30 m. Therefore, we assumed that the deep wells would describe a majority of the storage change, while shallow wells either represented changes in relatively small surficial or perched aquifer layers, or were well-connected and measured changes commensurate to those in nearby deep wells.

We estimated the net groundwater storage change over the High Plains aquifer between 2003 and 2013 to be -142 ± 8.35 km^3, with an average change of -12.9 ± 0.76 km^3 yr^{-1}. We note that these are different in statistical significance, direction and order of magnitude as compared to the results presented by *Richey et al.* [2015a]. The average storage change calculated for all the wells (including shallow wells) was within the error range predicted for the deep wells alone. Our results suggest that groundwater storage decreased in the aquifer as a whole, though large regions in the northern part of the aquifer show increased groundwater storage (Figure 1c). The volume increases in the northern region are not as great as the volume decreases in parts of the central and southern aquifer, resulting in an overall net decline of storage. Hydrologic conditions clearly vary across the aquifer system, which limits the meaningfulness of these spatially averaged results.

Using the same IDW method described above with monthly groundwater level data, we calculated the annual trend of groundwater storage anomalies to be -0.06 m yr^{-1}, suggesting an even greater trend of storage depletion (-27 km^3 yr^{-1}). The trend of storage is estimated to be -7.6 km^3 yr^{-1} using only the winter average groundwater levels. We have been unable to replicate a positive trend value using IDW or simple averaging of the groundwater records.

Previous studies using ground-based observations of the High Plains aquifer also found storage declines in recent years (Table 1). For example, *McGuire* [2007, 2009, 2011, 2013] indicated that groundwater storage changed at a rate of -9.36 km^3 yr^{-1} with a total loss of 93.62 km^3 between 2003 and 2013. *Konikow* [2013] used area-weighted, average specific yield of the aquifer (15.1%) and change in water level to calculate change in groundwater storage between 1900 and 2008. *Konikow* [2013] calculated storage change over the latter part of the study time period, 2000–2008, to be -81.8 km^3 (-10.2 km^3 yr^{-1}). While not exactly overlapping the study period of the present study, the annual change value is comparable.

Challenges in estimating groundwater storage declines in the High Plains with GRACE data were discussed by *Strassberg et al.* [2009] and *Longuevergne et al.* [2010]. These authors tested different GRACE data processing techniques and compared estimates of groundwater storage changes to ground-based measurements. *Breña-Naranjo et al.* [2014] tested three types of correction methods to modify GRACE-derived

Table 1. Calculated Recent Groundwater Storage Change in the High Plains Aquifer

Methods	Years of Study	Annual Rate of Storage Change ($km^3\ yr^{-1}$)	Citation
Groundwater level change and storativity	2003–2013	−9.36	*McGuire* [2007, 2009, 2011, 2013, 2014]
GRACE-derived total water storage minus in-situ soil moisture	2003–2006	−1.74	*Strassberg* [2009]
GRACE-derived total water storage minus simulated soil moisture	2003–2006	−2.49	*Strassberg* [2009]
Groundwater level change and storativity	2000–2008	−10.2	*Konikow* [2013]
GRACE-derived groundwater storage with a correction for irrigation	2003–2013	−11.4 ± 0.4	*Breña-Naranjo et al.* [2014]
GRACE-derived groundwater storage including recharge and use	2003–2013	+0.16 ± 0.46	*Richey et al.* [2015a]
Groundwater level change and storativity (1) Net change (2) Monthly trend (3) Winter trend	2003–2013	(1) −12.9 ± 0.76 (2) −24.3 (3) −7.65	Current study

storage and found a correction accounting for irrigation provided the best fit to ground observations. They reported a change in groundwater storage of $-125 \pm 4.3\ km^3$ ($-12.5 \pm 0.4\ km^3\ yr^{-1}$) from 2003 to 2013 based on the best correction method. *Alley and Konikow* [2015] discussed more generally the limitations of using GRACE data to evaluate groundwater resources.

Considering the previous analyses using GRACE data, we suggest there may be a systematic problem with GRACE estimates of groundwater storage change for the High Plains aquifer that do not explicitly account for irrigation and water stored in the vadose zone. We appreciate that interpolation methods using ground-based data are also subject to uncertainty, given nonuniform spatial sampling and the errors introduced by the interpolation technique followed by differencing of the results. The storage trend varies with input data set and the averaging method. Though our uncertainty associated with interpolation and differencing ground-based measurements ($\pm\ 0.76\ km^3\ yr^{-1}$) was larger than that of *Richey et al.* [2015a] ($\pm\ 0.46\ km^3\ yr^{-1}$), the difference between the recent estimates of storage change and those of comparable studies are still significant. Since the GRACE estimates are based in part on a deconvolution of an inherently large scale signal that is smoother and would have less variability than that encountered in estimates based on individual wells, these estimates may indeed report lower uncertainty in the trend. However, they may not be representative of the underlying trends, i.e., they may be marked by biases over a specific estimation domain which exhibits heterogeneous trends.

GRACE is helping to address hydrologic questions at large scales and in regions lacking available ground-based measurements. We ask how in general such estimates can be best constrained and interpreted. This note is intended to stimulate that dialog.

Acknowledgments
The work presented here was supported in part by NSF grant 1360446 (Water Sustainability and Climate Category 3) and the 1896 Pilot Project from University of Chicago.

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