Groundwater Depletion During Drought Threatens Future Water Security of the Colorado River Basin

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Abstract

Streamflow of the Colorado River Basin is the most over-allocated in the world. Recent assessment indicates that demand for this renewable resource will soon outstrip supply, suggesting that limited groundwater reserves will play an increasingly important role in meeting future water needs. Here we analyze nine years (December 2004 to November 2013) of observations from NASA's GRACE mission and find that during this period of sustained drought, groundwater accounted for 50.1 km^3 of the total 64.8 km^3 of freshwater loss. The rapid rate of depletion of groundwater storage (-5.6 ± 0.4 km^3 yr^{-1}) far exceeded the rate of depletion of Lakes Powell and Mead. Results indicate that groundwater may comprise a far greater fraction of Basin water use than previously recognized, in particular during drought, and that its disappearance may threaten the long-term ability to meet future allocations to the seven Basin states.

Introduction

Over a decade of drought in the Colorado River Basin (Basin; Figure 1) has exposed the vulnerability [Bureau, 1975; Barnett and Pierce, 2008] of the most over-allocated river system in the world [Christensen *et al*., 2004]. Recently, the U. S. Bureau of Reclamation acknowledged the potential challenges [Bureau, 2012] to meeting future surface water allocations to the 7 Basin states (Figure 1), noting that the contribution of local supplies, including groundwater withdrawals, will be required to offset anticipated shortages. While the need to exploit groundwater resources to meet Basin water demands has long been recognized [Bureau, 1975], withdrawals required to meet current demands remain undocumented and are uncertain in the future. In particular, water management under drought conditions focuses on surface water resources [Basin Interim Guidelines, 2007] without a regulatory framework to manage groundwater withdrawals outside of "river aquifer" systems [Leake *et al*., 2013]. At question is the potential impact of solely managing surface water allocations and diversions in the Basin, without regard to groundwater loss, on meeting future water demands.

The ability to observe changes in water resources at large scales has been greatly facilitated by the deployment of recent Earth-observing satellites. One such satellite mission, the NASA Gravity Recovery and Climate Experiment (GRACE) [Tapley *et al*., 2004], has measured temporal variations in Earth's gravity field since March 2002. These observations are now routinely applied to estimate monthly changes in terrestrial, or total land water storage (i.e., all of the snow, surface water, soil moisture and groundwater) in regional areas that are 200,000 km^2 or larger [Wahr *et al*., 2004] (Figure 2). Several studies have now demonstrated that GRACE observations, when combined with coincident datasets for snow water equivalent (SWE), surface water storage and soil water content in a mass balance, can quantify changes in groundwater storage with sufficient accuracy [e.g., Rodell *et al*., 2009; Famiglietti *et al*., 2011] to influence regional water management decisions [Famiglietti and Rodell, 2013].

Our goal in this report is to identify changes in freshwater storage, including surface reservoir and groundwater storage, to assess the influence of conjunctive surface water and groundwater use on water availability in the Colorado River Basin during the recent drought. We evaluate terrestrial water storage anomalies (TWSA) using GRACE observations during a 9-year period (December 2004 to November 2013) that begins 4 years into a prolonged drought in the southwestern United States, after water levels in Lakes Powell and Mead had declined precipitously [Piechota *et al*., 2004] (see Methods). In particular, we estimate changes in groundwater storage during the 9-year drought period, when reservoir volumes were intensively managed to maintain hydropower production and to meet surface water allocations to the Basin states.

Methods

We used Release-05 of the University of Texas Center for Space Research GRACE data [Tapley *et al*., 2007] (ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR/RL05/). Average water storage changes for the Colorado River Basin were computed as anomalies of terrestrial water storage in equivalent water height (in mm, converted to km^3 here using the area of the study basins) following [Swenson and Wahr, 2009] (Figure 2). Processing methods include filtering GRACE data to reduce noise [Swenson and Wahr, 2006], and later restoring the associated lost signal over a specific region by scaling the data correctively [Velicogna and Wahr, 2006]. This processing results in estimates of satellite measurement error and leakage error from out-of-basin signal, both of which are included in a Basin-specific time-invariant error estimate [Wahr *et al*., 2006]. Figure 2 shows Basin time series of terrestrial water storage changes from January 2003 to November 2013, nearly the complete available GRACE data record.

Because our focus here is on quantifying groundwater storage changes versus surface water storage changes during drought, we restrict our analyses to the 9-year period from December 2004 to November 2013. Prior to December 2004, the Basin had experienced 4 additional years of drought, effectively limiting surplus inflows that replenish Lakes Powell and Mead. This caused steep declines in reservoir storage prior to the December 2004. Late 2004 also marked the beginning of a clear drought signal in the GRACE data, relative to its launch date in March 2002 (Figure 2).

To assess the accuracy of the GRACE data used here, we performed independent water budget analyses using regional precipitation (*P*) data from the PRISM system [Daly *et al*., 2008] (http://prism.oregonstate.edu/recent/), satellite-based evapotranspiration from MODIS (*ET*) [Tang *et al*.,2009] and U. S. Bureau of Reclamation dam releases (*Q*) (usbr.gov; accessed 12/2013) on the Colorado River. Uncertainty in the water balance estimate [Rodell *et al*., 2004a; Rodell *et al*., 2004b] was calculated assuming relative errors of 15 percent for P [Jeton *et al*., 2005] and 5 percent in Q [Rodell *et al*., 2004b]. A 15% bias on daily ET was determined in [Tang *et al*., 2009]; we assume the relative error increases to 25% on a monthly time scale. We computed monthly storage changes, dS/dt, as P – ET – Q, and compared them to dS/dt derived from the GRACE terrestrial water storage anomalies using a discrete backwards difference. Results illustrate good agreement between dS/dt derived from the water budget and that observed by GRACE, for the entire Basin, and the Upper and Lower Basins (Figure S1). Our comparisons were limited to March 2005 to March 2010 owing to the availability of ET estimates. Numerous additional studies have shown strong correspondence between GRACE water storage changes, hydrologic fluxes and observations [see e.g. Swenson *et al*., 2006; Famiglietti *et al*., 2011].

Accessible water storage changes (the combination of surface reservoir and groundwater storage changes) in the Basin are quantified using a water mass balance approach. Studies [e.g., Rodell and Famiglietti, 2002; Rodell *et al*., 2009; Famiglietti *et al*., 2011, Scanlon et al., 2012] have shown that GRACE-observed water storage changes, in combination with additional data sets, can be used to isolate individual components of the terrestrial water balance. We assume that the total water storage in a region is comprised of soil moisture (SM), snow water equivalent (SWE), surface water (SW) and groundwater (GW):

$$TWS_t = SM_t + SWE_t + SW_t + GW_t \qquad (1),$$

where the subscript *t* indicates a function of time, and changes in these components balance in their sum. We apply GRACE observations of variations from the long-term mean of this total with estimates of soil moisture and SWE to quantify changes in accessible water. We simplify Equation (1) by defining accessible water as the sum of groundwater and surface water storage:

$$\Delta AW_t = TWSA_t - \Delta SWE_t - \Delta SM_t \qquad (2),$$

where *Δ* indicates a variation from the time-mean in an individual variable, and TWSA is the terrestrial water storage anomaly.

Soil moisture anomalies in Equation (2) were estimated from the NASA Global Land Data Assimilation System (GLDAS) [Rodell *et al*., 2004a] (http://disc.sci.gsfc.nasa.gov/) due to the lack of observational soil moisture data on large scales, and for consistency with previous studies [Rodell *et al*., 2009, Famiglietti *et al*., 2011]. We average the results of three land-surface models from GLDAS (VIC [Liang *et al*., 1994], Noah [Chen *et al*., 1996] and CLM2 [Dai *et al*., 2003]), and apply the mean monthly standard deviation as an error estimate based on model structural biases (Figure S2).

Data obtained from the Snow Data Assimilation System (SNODAS) [NOHRSC, 2004] (http://nsidc.org/data/polaris/) were used for SWE in Equation (2) (Figure S2). SNODAS is the only gridded observation-based SWE product that assimilates ground, airborne and satellite snow observations into its model structure and consequently has been used to represent SWE in other regional hydrologic studies [Famiglietti *et al*., 2011; Barlage *et al*., 2010]. Previous studies documented error of approximately 11% between SNODAS and snowpit observations in the Rocky Mountains [Rutter *et al*., 2008] and 15% error for basin-wide analysis [Famiglietti *et al*., 2011]. For this study, we assume 20% error due to the topographic and terrain heterogeneity throughout the Basin [USGS, 2004].

We further separated the components of accessible water (Figure S3) into surface water reservoir storage and groundwater storage (Figure 3). Reported reservoir storage time series from Lake

Powell and Lake Mead were obtained from the U. S. Bureau of Reclamation [usbr.gov; accessed 12/2013]. We assume Lakes Powell and Mead account for the majority of the observed surface water change as they comprise approximately four times the annual flow of the river and make up 85% of surface water in the Basin [Rajagopalan *et al*., 2009]. USGS errors for hydrologic measurements ranging from "excellent (5%)" to "fair (15%)" [Sauer and Meyer, 1992] were used to provide error estimates for surface water reservoir storage. A two sample t-test could not reject the null hypothesis that sample means were different using the USGS ranges in error, and throughout the rest of the analysis we used a 10% error estimate for the surface water reservoir storage time series.

We rearranged Equation (1) to isolate the contribution of groundwater storage changes (Figure 3) to changes in total water storage (Figure 2). We used the reservoir storage changes in Lake Mead and Lake Powell with soil moisture and snow water equivalent data as described above:

$$\Delta GW_t = TWSA_t - \Delta SWE_t - \Delta SM_t - \Delta SW_t \qquad (3),$$

where ΔSW_t indicates surface water anomaly from the reservoirs (Lakes Powell and Mead combined for the entire Basin; Lake Powell for the Upper Basin and Lake Mead for the Lower Basin). Equation (3) was solved each month, and errors in the groundwater storage were estimated by propagating the errors of *TWSA*, *SM*, *SWE* and *SW* following Rodell *et al*. [2004b].

We compared our GRACE-based estimates of groundwater storage changes to groundwater level observations at 74 monitoring wells located throughout the basin. These data were obtained from the USGS (http://groundwaterwatch.usgs.gov/Net/OGWNetwork.asp?ncd=crn) and from the Arizona Department of Water Resources (ADWR; https://gisweb.azwater.gov/waterresourcedata/GWSI.aspx, accessed 5/2014). The selection of wells for comparison was limited to locations with observations that were concurrent with GRACE. Of these, 7 USGS and 65 ADWR were located in the Lower Basin, and 2 USGS monitoring wells were identified in the Upper Basin. GRACE-derived groundwater estimates generally capture the observed behavior well (See Results and Figure 4).

The trends reported in the text and summarized in Table 1 were estimated employing a method that accounts for residual serial correlation and time series error, and sub-basin trends may not sum linearly [Johnston and DiNardo, 1997]. We identified several significant trends over the entire 108-month time period studied, and in shorter time periods, from December 2004-January 2010 and from February 2010-November 2013 (Table 1).

Results

We find that during the 108-month study period, the entire Colorado River Basin lost a total of 64.8 km^3 of freshwater (-7.2 ± 0.8 km^3 yr^{-1}, where ± represents the standard error of the slope coefficient) (Figure 2A) with a more severe rate of loss since February 2010 (-19.2 ± 2.1 km^3 yr^{-1}). The Upper Basin (Figure 1) lost 21.6 km^3 of water during the entire study period, with more severe loss rates after February 2010 (-11.5 ± 2.0 km^3 yr^{-1}) (Figure 2B). Study period losses in the Lower Basin of 34.7 km^3 were greater than in the Upper Basin, and declined at a faster rate (-3.9 ± 0.5 km^3 yr^{-1}) (Figure 2C). All trends are listed in Table 1. As described in the Methods section, we compared our GRACE-derived water storage estimates to independent water balances for the entire, Upper and Lower Basins with good agreement (Figure S1). This comparison lends additional confidence to the results reported here.

Further analysis of trends in groundwater storage (Figure S4) revealed two distinct phases of depletion prior to and following 2009-2010. From December 2004 to January 2010, groundwater storage declined more rapidly in the Lower Basin (-4.1 ± 0.6 km^3 yr^{-1}) compared to the Upper Basin, (-1.9 ± 0.8 km^3 yr^{-1}). Groundwater losses from February 2010-November 2013 were found to be even greater in the Upper (-6.1 ± 1.5 km^3 yr^{-1}) and Lower Basins (-5.8 ± 0.9 km^3 yr^{-1}).

A brief recovery in groundwater storage is apparent from June 2009-March 2010, when moderately wetter conditions provided a combination of potential groundwater recharge and temporarily alleviated the need to augment surface water supplies. The steepest rate of groundwater storage decline (in the Upper Basin in 2013) follows exceptional drought conditions in 2012 and record low Rocky Mountain snowpack (US Drought Monitor, 2012; see Figure S2). Such behaviors highlight the close connection between surface water availability and groundwater use [Famiglietti *et al*., 2011].

We find that water losses throughout the Basin are dominated by the depletion of groundwater storage (Figure 3). Renewable surface water storage in Lakes Powell and Mead showed no significant trends during the 108-month study period, more recent declines (since 2011) and currently low (<50% of capacity) storage levels notwithstanding. Groundwater storage changes, however, accounted for the bulk (Table 1) of the freshwater losses in the entire Basin (50.1 km^3;

-5.6 ± 0.4 km^3 yr^{-1}), the majority of which occurred in the Lower Basin (Figure 3C). As mentioned in Methods, we examined USGS and ADWR monitoring wells in the Basin during the study period. The observed behavior in these wells showed good agreement with our GRACE-based estimates. Figure 4 shows the comparisons for the USGS wells. A sen slope trend comparison to the ADWR wells showed that measured groundwater table changes closely matched our GRACE-based estimates. These comparisons help confirm the groundwater depletion rates reported here.

Discussion

Drought in the Basin has effectively limited the surplus inflows that replenish Lakes Powell and Mead since the beginning of the 9-year study period, while active surface water management has prevented further declines in reservoir levels. Consequently, reservoirs show insignificant trends in storage levels (-0.9 ± 0.6 km^3 yr^{-1}), while groundwater has been significantly depleted (-5.6 ± 0.4 km^3 yr^{-1}). The vast difference may well be attributed to the regulatory framework already in place to manage surface waters, and to the general need for more active and enforceable groundwater management throughout the Basin, in particular, during drought.

The large, net negative change in groundwater storage is a clear indication that groundwater withdrawals are not balanced by recharge and must be greater than the observed depletion rate. The additional loss of 5.6 km^3 yr^{-1} of groundwater, relative to annual Basin surface water allocations of 18 km^3 yr^{-1}, indicates further that Basin water supply was over-allocated by at least 30% during the study period. Thus, we observe that groundwater is already being used to fill the gap between Basin demands and the annual, renewable surface water supply.

Groundwater is typically used to augment sparse surface water supplies in the arid, Lower Basin, and across the entire Basin during drought [Hutson *et al*., 2004; Kenny *et al*., 2009]. More generally, water managers around the world rely on groundwater to mitigate the impacts of drought on water supply [LeBlanc *et al*., 2008; Famiglietti *et al*., 2011; Famiglietti and Rodell, 2013; Taylor *et al*., 2013]. Groundwater represents the largest supply of water for irrigation within the Basin [Hutson *et al*., 2004; Kenney *et al*., 2009], while irrigated acreage in the Basin has increased during our study period [Ward and Pulido-Velazquez, 2008; Cohen *et al*., 2013]. Furthermore, prolonged drought across the southwestern U. S. has resulted in overreliance on groundwater to minimize impacts on public water supply [Famiglietti and Rodell, 2013]. Long-term observations of groundwater depletion in the Lower Basin (e. g. in Arizona, - despite groundwater replenishment activities regulated under the 1980 Groundwater Code - and in Las Vegas [Konikow, 2013]) underscore that this strategic reserve is largely unrecoverable by natural means, and that the overall stock of available freshwater in the Basin is in decline.

Future water management scenarios that account for both population growth and climate change also point to the inability of reservoir storage alone to meet Basin allocations [Barnett and Pierce, 2008; Bureau, 2012]. These scenarios indicate that additional stresses will be placed upon the groundwater system, beyond those described here, to meet future Basin water demands. We believe that the combination of reduced surface water availability resulting from decreasing future snowpack [Barnett *et al*., 2008] and groundwater depletion poses a significant threat to the long-term water security of the region. As groundwater supplies reach their limits, the ability to supply freshwater during drought, or to fill the predicted, increasing gap between supply and demand [Bureau, 2012] will be severely constrained.

The challenge to policy makers and water managers in the Colorado River Basin is to reliably meet freshwater demand under these dynamic conditions. Our work suggests that a conjunctive surface water and groundwater management plan is essential for sustainable water management in the Basin. Despite commendable efforts to craft solutions to meet required surface water allocations [Bureau, 2012], consideration of the ability of groundwater withdrawals to meet current and future demands remain dormant. We hope that heightened awareness of the rates of Basin groundwater depletion highlighted here will foster urgent discussion on conjunctive management solutions required to ensure a sustainable water future for the Colorado River Basin and for the western United States.

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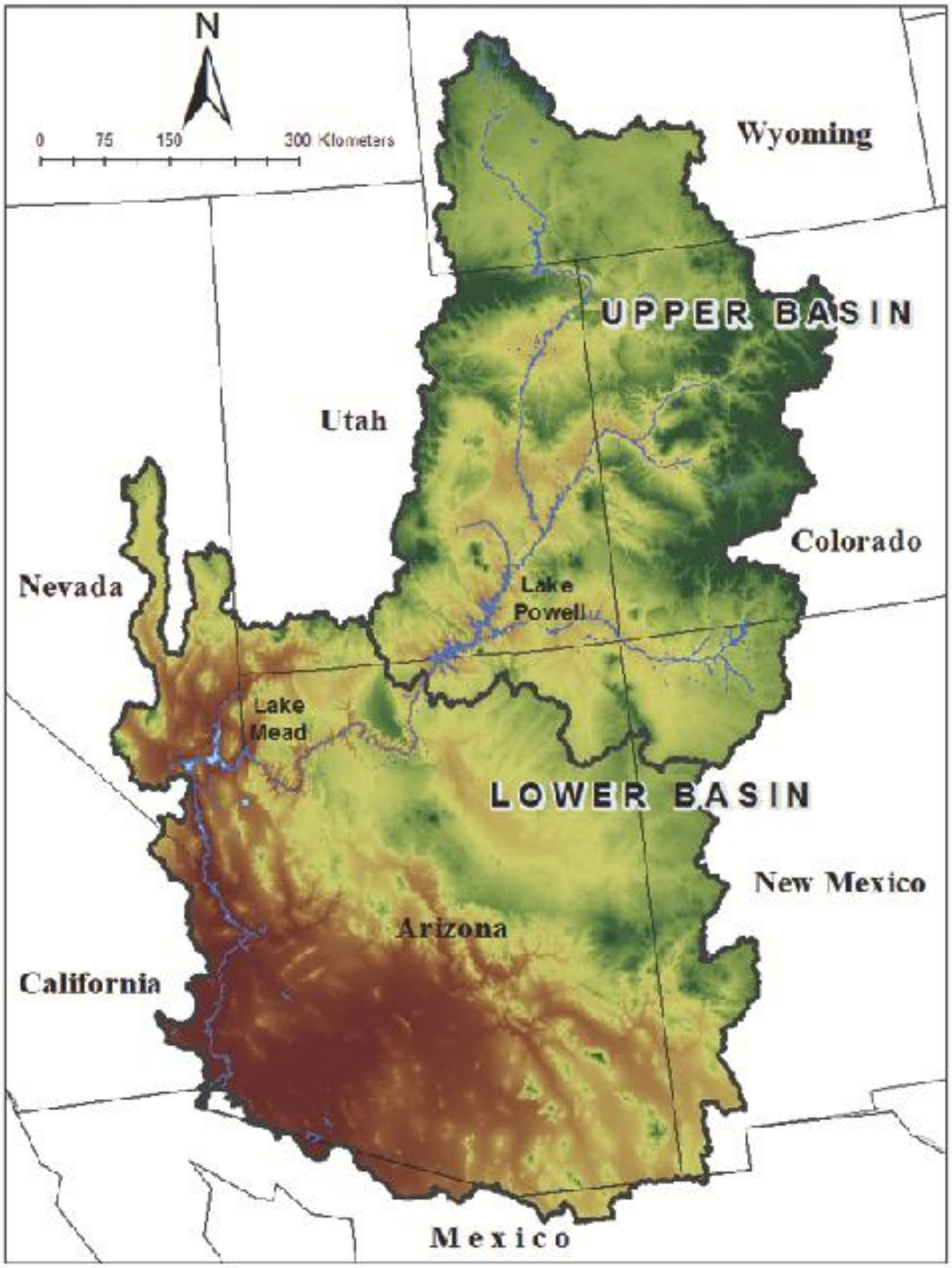

Figure 1. The Colorado River Basin of the western United States. State and international boundaries in light gray. Green and brown colors represent high and low elevations, respectively [McKay *et al*., 2012]. The Upper Basin is that portion of the Basin upstream of Lake Powell. The Lower Basin is the remainder of the basin downstream of Lake Powell. Basin outlines are in dark gray. The river, its main tributaries and Lakes Powell and Mead are shown in blue.

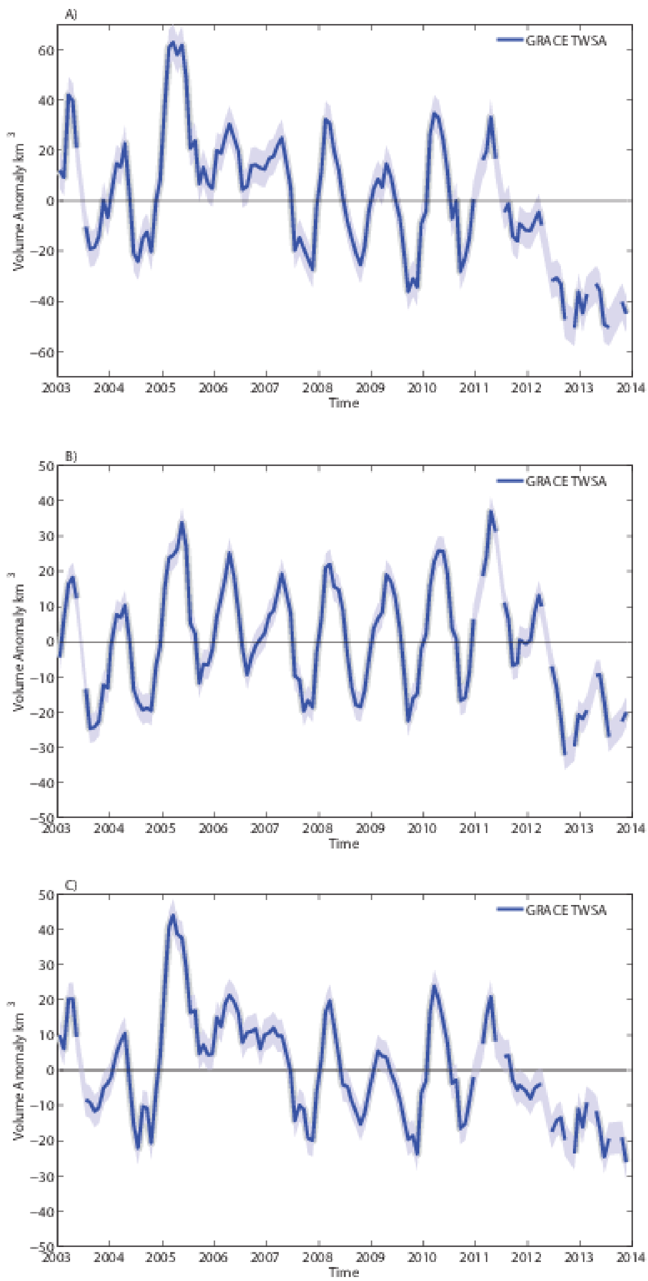

Figure 2. Monthly anomalies (deviations from the mean of the study period) of total water storage (TWSA) for (A) the entire Basin; (B) the Upper Basin; and (C) the Lower Basin, from January 2003 to November 2013 (i.e. the full GRACE RL05 record available at writing). The three TWSA estimates were calculated independently using basin specific scaling. Anomaly errors are shown in light blue shading. There are inconsecutive gaps in the GRACE data record,

increasing in number towards the end of the time period due to recent declines in satellite power supply. Subsequent analyses focus on the period of prolonged drought extending from December 2004 to November 2013.

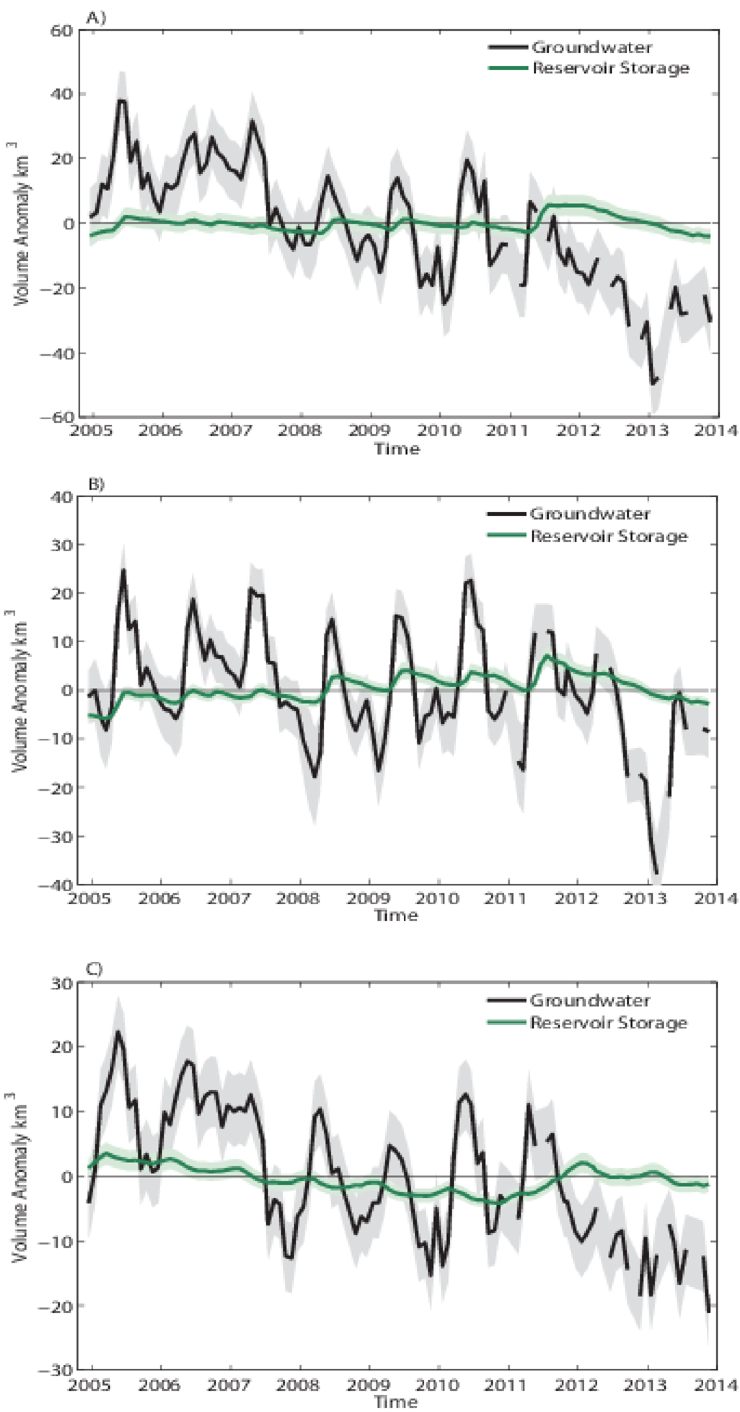

Figure 3. Monthly anomalies (km^3) of groundwater storage (black) and of surface reservoir storage (green) for (A) the entire Basin (trend: -5.6 ± 0.4 km^3 yr^{-1}) and Lakes Powell and Mead combined (trend: -0.9 ± 0.6 km^3 yr^{-1}); (B) the Upper Basin (trend: -1.7 ± 0.4 km^3 yr^{-1}) and Lake

Powell (trend: -0.6 ± 0.6 km^3 yr^{-1}); and (C) the Lower Basin (trend: -2.6 ± 0.3 km^3 yr^{-1}) and Lake Mead (trend: -0.1 ± 0.6 km^3 yr^{-1}), from December 2004 to November 2013. Anomaly errors are shown in light gray shading for groundwater storage and in light green shading for reservoir storage. All trends are summarized in Table 1.

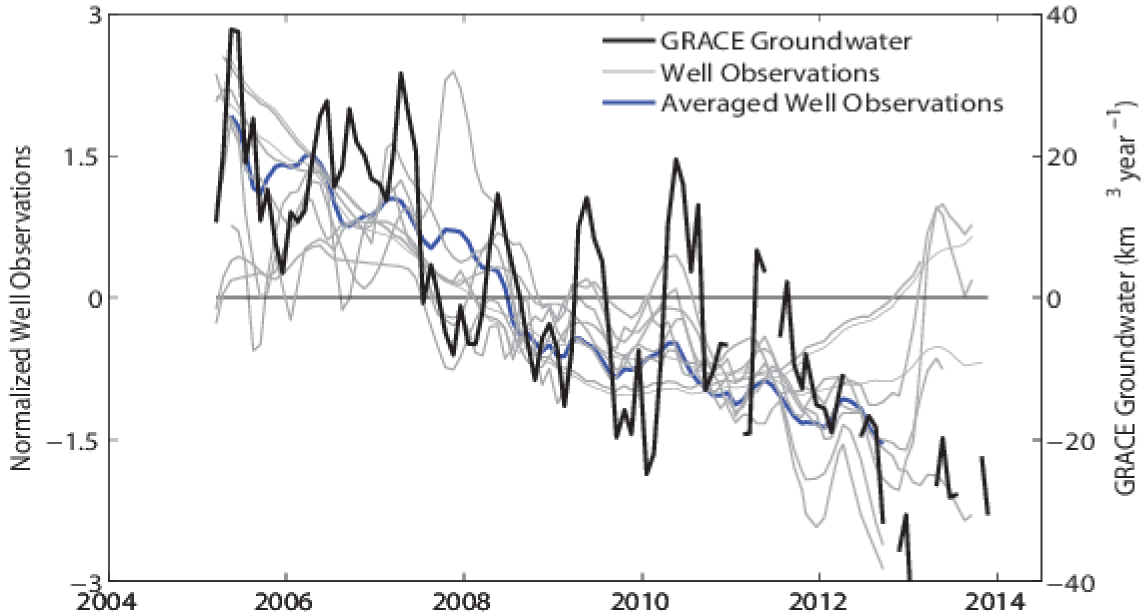

Figure 4. Entire Basin comparison between GRACE groundwater storage anomalies (black line) in km^3 and monthly USGS well observations (blue line is average of gray lines). Because specific yield information is not available for all wells, we normalize each well time series by its standard deviation and then average (in blue). Selected well observations were only available from March 2005 to October 2012; thus, we calculated the average over this time period.

Table 1. Trends in water budget components were calculated employing a method which adjusts a linear model for residual serial correlation and time series error [Johnston and DiNardo, 1997]. The approach identified several significant trends (shown by white cells) in accessible water (AW) in the Basin over the entire time period from December 2004-November 2013 and a piecewise trend analysis conducted from December 2004-January 2010 and from February 2010-November 2013. Basin TWSA estimates are calculated independently and there is no assumption that sub-basin trends will sum linearly.

Trends in Terrestrial Water in km^3/year

Time	Component	Entire CRB	Upper CRB	Lower CRB
Entire Time Period	TWSA	-7.18 ± 0.75	-2.34 ± 0.59	-3.90 ± 0.47
December 2004-November 2013	SWE	0.00 ± 0	0.00 ± 0	0.00 ± 0
	SM	-1.29 ± 1.8	-0.861 ± 0.85	-0.905 ± 0.24
	Reservoirs	-0.865 ± 0.60	-0.638 ± 0.63	-0.057 ±0.63
	GW	-5.56 ± 0.44	-1.66 ± 0.40	-2.63 ± 0.30
	AW	-5.40 ± 0.47	-1.13 ± 0.44	-3.02 ± 0.30
Time				
Piecewise Analysis 1	TWSA	-10.6 ± 1.4	-3.41 ± 1.1	-7.49 ± 0.90
December 2004-January 2010	SWE	0.00 ± 0	0.00 ± 0	0.00± 0
	SM	-2.67 ± 4.2	-1.74 ± 1.9	-1.45 ± 2.2
	Reservoirs	-0.428 ± 0.34	1.31 ± 0.13	-1.20 ± 0.05
	GW	-6.23 ± 0.91	-1.91 ± 0.80	-4.06 ± 0.60
	AW	-6.29 ± 0.96	-1.37 ± 2.2	-5.27 ± 0.62
Time				
Piecewise Analysis 2	TWSA	-19.2 ± 2.1	-11.5 ± 2.0	-9.14 ± 1.3
February 2010-November 2013	SWE	0.00 ± 0	0.00 ± 0	0.00 ± 0
	SM	-6.82 ± 1.2	-2.88 ± 0.76	-3.64 ± 0.62
	Reservoirs	-8.42 ± 4.7	-3.22 ± 1.2	-0.085 ± 2.0
	GW	-10.9 ± 1.5	-6.10 ± 1.5	-5.83 ± 0.89
	AW	-11.2 ± 1.6	-7.48 ± 1.6	-4.85 ± 0.90
Significant Trend				
Trend not significant				