Supporting Information

Hydrologic Implications of GRACE Satellite Data in the Colorado River Basin

Bridget R. Scanlon, Zizhan Zhang, Robert C. Reedy, Donald R. Pool, Himanshu Save, Di Long, Jianli Chen, David Wolock, Brian D. Conway, and Daniel Winester

Table of Contents

List of Figures

List of Tables

Section 1: The Law of the River

The Colorado River Basin is managed according to the "Law of the River" (http://www.usbr.gov/lc/region/g1000/lawofrvr.html) which includes various compacts, laws, and regulatory guidelines. The following summarizes the important components of the Law of the River. Because most of the flow in the basin originates in the UCRB but most of the demand is in the LCRB, there were concerns that water would be primarily allocated to lower Basin states. The Colorado River Compact of 1922 apportioned Colorado River water equally between the UCRB and LCRB (7.5 maf/yr each, 9.2 km^3/yr). The Boulder Canyon Project Act of 1928 apportioned the 7.5 maf (9.2 km^3) among the Lower Basin states (Arizona, 2.8 maf [3.5 km^3], California, 4.4 maf [5.4 km^3], and Nevada, 0.3 maf [0.4 km^3]). The Mexican Water Treaty of 1944 committed 1.5 maf/yr (1.8 km^3/yr) to Mexico. The Upper Colorado River Basin Compact of 1948 apportioned the 7.5 maf (9.2 km^3) among Colorado (3.9 maf [4.8 km^3]), New Mexico (2.0 maf [2.5 km^3]), Utah (1.0 maf [1.2 km^3]) and Wyoming (0.5 maf [0.6 km^3]) and additional 0.05 maf (0.06 km^3) to the portion of Arizona in the UCRB. The total allocation is 16.5 maf (20.3 km^3). The Colorado River Basin Project Act of 1967 authorized construction of the Central Arizona Project (CAP) to deliver water from the Colorado River to central Arizona and made the CAP water supply subordinate to the Colorado River appropriation to California during periods of water shortages. The Coordinated Long-Range Operation of the Colorado River Reservoirs of 1970 (amended in March 2005) provided for the coordinated operation of reservoirs in the UCRB and LCRB and established conditions for water releases from Lake Powell and Lake Mead.

Over-allocation of the Colorado River (20.3 km^3) results from the allocation being determined in 1922 after a period of above average flow (22.2 km^3/yr) relative to the current ~100 yr average flow (18.3 km^3/yr). The past 15 years since 2000 have been extremely dry with average flow of 15.2 km^3/yr (2000 – 2014) at Lee's Ferry and reservoir storage sharply declined from a peak of 66.5 km^3 (2000) to 40.1 km^3 (2004). Current reservoir storage (38.7 km^3, 2014) represents 44% of reservoir capacity (87.2 km^3) and 69% of long-term reservoir storage (56.1 km^3), raising concerns about water reliability.

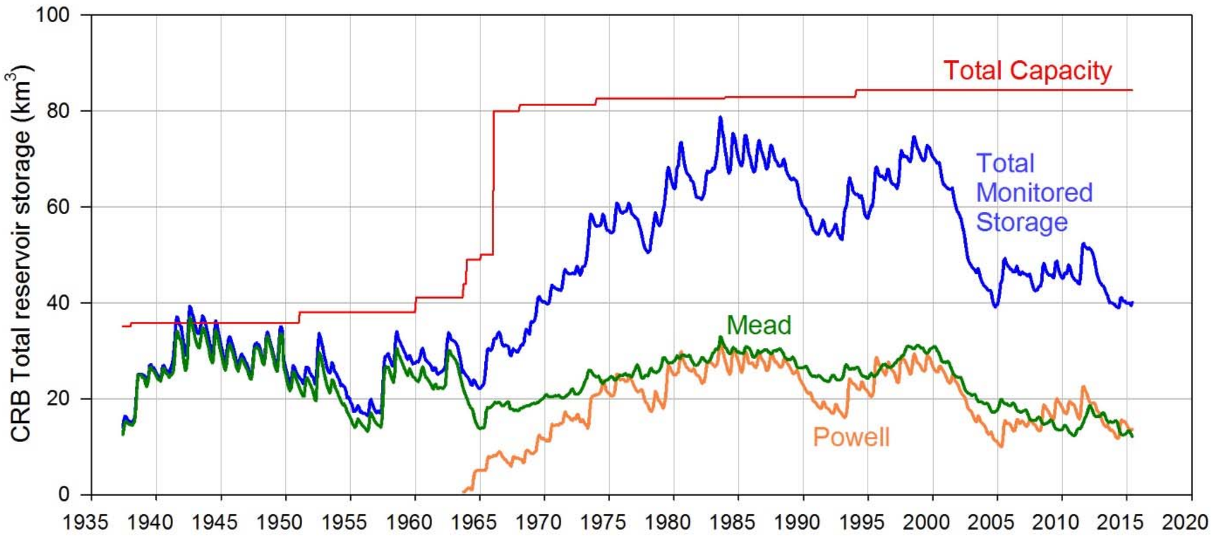

Figure S1. Evolution of reservoir storage capacity and monthly total (monitored) water storage. Storage for Lake Mead and Lake Powell are also shown separately. Monitored storage represents ~ 95% of total UCRB reservoir capacity and 98% of total LCRB reservoir capacity.

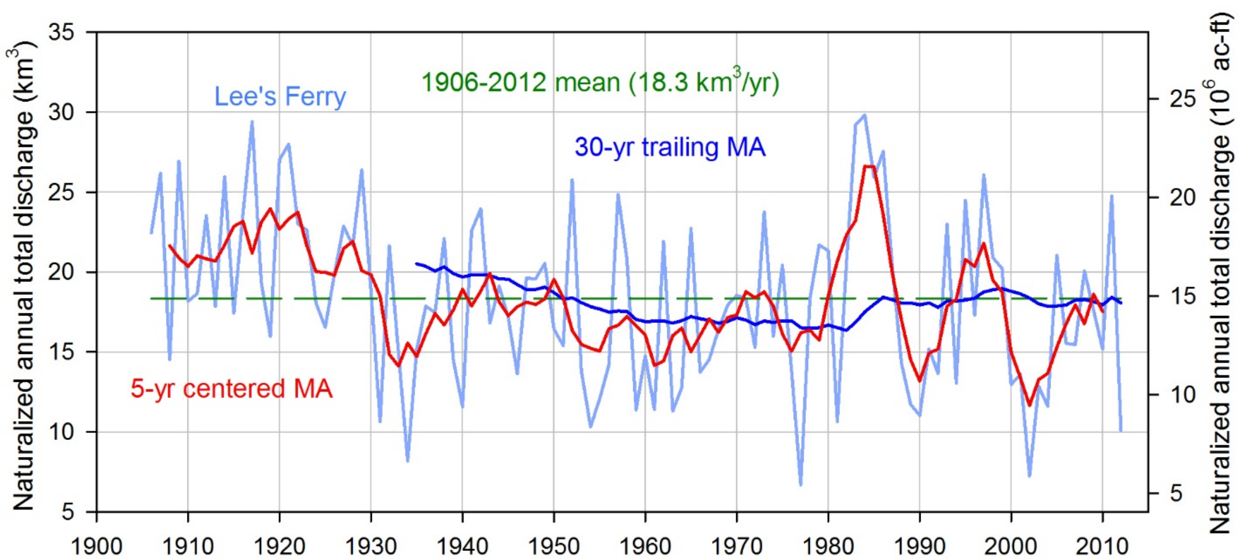

Figure S2. Naturalized discharge for the Colorado River at Lee’s Ferry, Arizona. The long-term mean and different moving average (MA) values are also shown.
http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html

Section 2. Data Sources

Websites for data sources are listed below:

SNODAS data: http://sidc.org/dat/polaris/
Precipitation (rain + melted snow): PRISM http://www.prism.oregonstate.edu/.
Drought conditions: http://droughtmonitor.unl.edu/
Drought indices: SPI, PDSI, NCDC, http://www.esrl.noaa.gov/psd/data/usclimdivs/
Soil Moisture Storage: NLDAS (NOAH, MOSAIC, and VIC LSMs) /ldas.gsfc.nasa.gov/nldas/
GLDAS (NOAH, MOSAIC, VIC, and CLM LSMs) http://ldas.gsfc.nasa.gov/gldas/
Reservoir storage: www.usbr.gov/UC/ or /LC.
Flow at Lee's Ferry downstream of Lake Powell http://www.usbr.gov/lc/region/g4000/NaturalFlow/
Area averaged streamflow for UCRB (HUC 14) and LCRB (HUC 15) (http://waterwatch.usgs.gov/new/).
Stream gage data (http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml).
Groundwater level monitoring data were obtained from the Arizona Dept. of Water Resources (ADWR) Groundwater Site Inventory (GWSI; https://gisweb.azwater.gov/waterresourcedata/GWSI.aspx).
Water deliveries from the Colorado River to central Arizona were obtained from the Arizona Dept. of Water Resources (ADWR) Central Arizona Project (http://www.cap-az.com/).
Ground-based gravity data for synoptic surveys at ~ 200 stations were obtained from the ADWR

Data on monthly SnWS were obtained from SNODAS (SNOw Data Assimilation System) (Fig. S3). SNODAS is a gridded product that includes input from satellites, airborne, and ground-based observations and are available from 2002 to 2014. SWE data prior to GRACE period (1980 - 2001) are based on Snotel gauges located throughout the higher elevation areas of the UCRB. Snotel SWE data were converted to estimated SnSW volumes by area-weighting the mean SWE values of stations over areas of similar elevation using 500-ft (150 m) elevation bins starting at 8,000 ft (2,440 m). Time series of monthly precipitation (rain + melted snow) was obtained from PRISM for the period of record (1895 – 2014). Estimates of monthly SMS were obtained from GLDAS (NOAH, MOSAIC, VIC, and CLM) LSMs and NLDAS (NOAH, MOSAIC, and VIC) LSMs.

Drought indices were evaluated to determine the temporal extent of drought using the Palmer Drought Severity Index (PDSI) and 12 month Standardized Precipitation Index (SPI12). The PDSI data were obtained for the climate divisions, spatially weighted according to the UCRB and LCRB from the National Climate Data Center (NCDC). Data on teleconnections include El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO).

Water storage for major reservoirs on the Colorado River were obtained from the Bureau of Reclamation. Data on natural flows downstream of Lake Powell for the Lee's Ferry gage were also obtained from the Bureau of Reclamation. Area averaged streamflow for Hydrologic Unit Code (HUC) 14 that corresponds to the UCRB and for HUC 15 (LCRB), that includes regulated and unregulated basins, was obtained from the USGS WaterWatch site.

Groundwater level monitoring data were obtained from the Arizona Dept. of Water Resources (ADWR) Groundwater Site Inventory (GWSI). Ground-based gravity data for synoptic surveys at ~ 200 stations were obtained from the Arizona Dept. of Water Resources (Fig. S4). Data on water withdrawal and consumption for counties that make up the UCRB and LCRB were obtained from the USGS water use database (Maupin et al., 2014). Water deliveries from the Colorado River to central Arizona were obtained from the Arizona Dept. of Water Resources (ADWR) Central Arizona Project. Time series of deliveries of Colorado River water within and exports outside of the basins were obtained from Bureau of Reclamation consumptive use and losses reports.

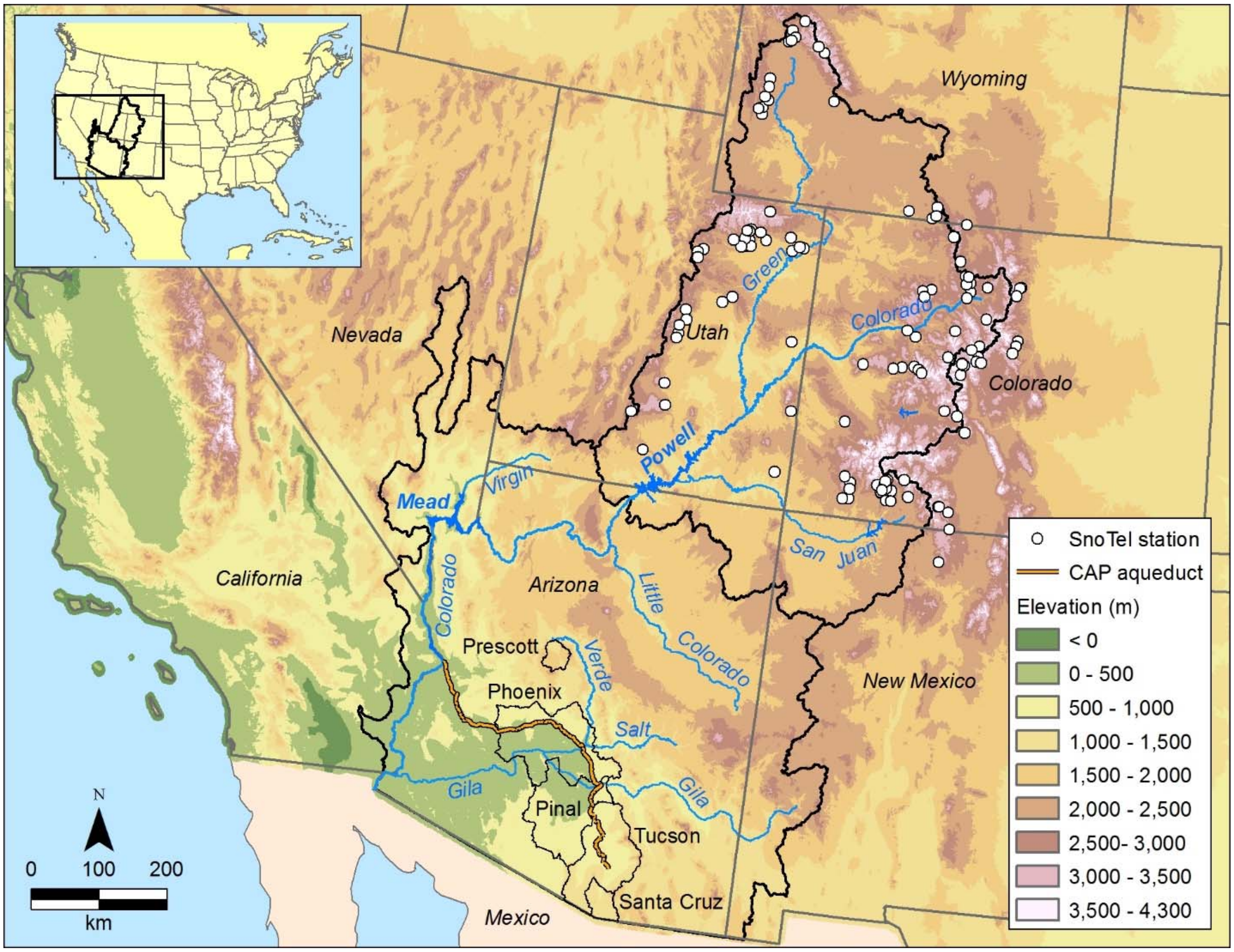

Figure S3. Digital elevation model (DEM) of the Colorado River Basin and surrounding regions. The Upper and Lower basins are outlined. Within the lower basin, the outlines for the Prescott, Phoenix, Pinal, Tucson, and Santa Cruz Aquifer Management Area (AMA) regions are shown. The river system and major reservoirs are also shown along with the Central Arizona Project (CAP) aqueduct and the SNOTEL snowpack monitoring network in the Upper basin and adjacent areas. (DEM source: http://www.prism.oregonstate.edu/, SNOTEL source: http://www.wcc.nrcs.usda.gov/snow/)

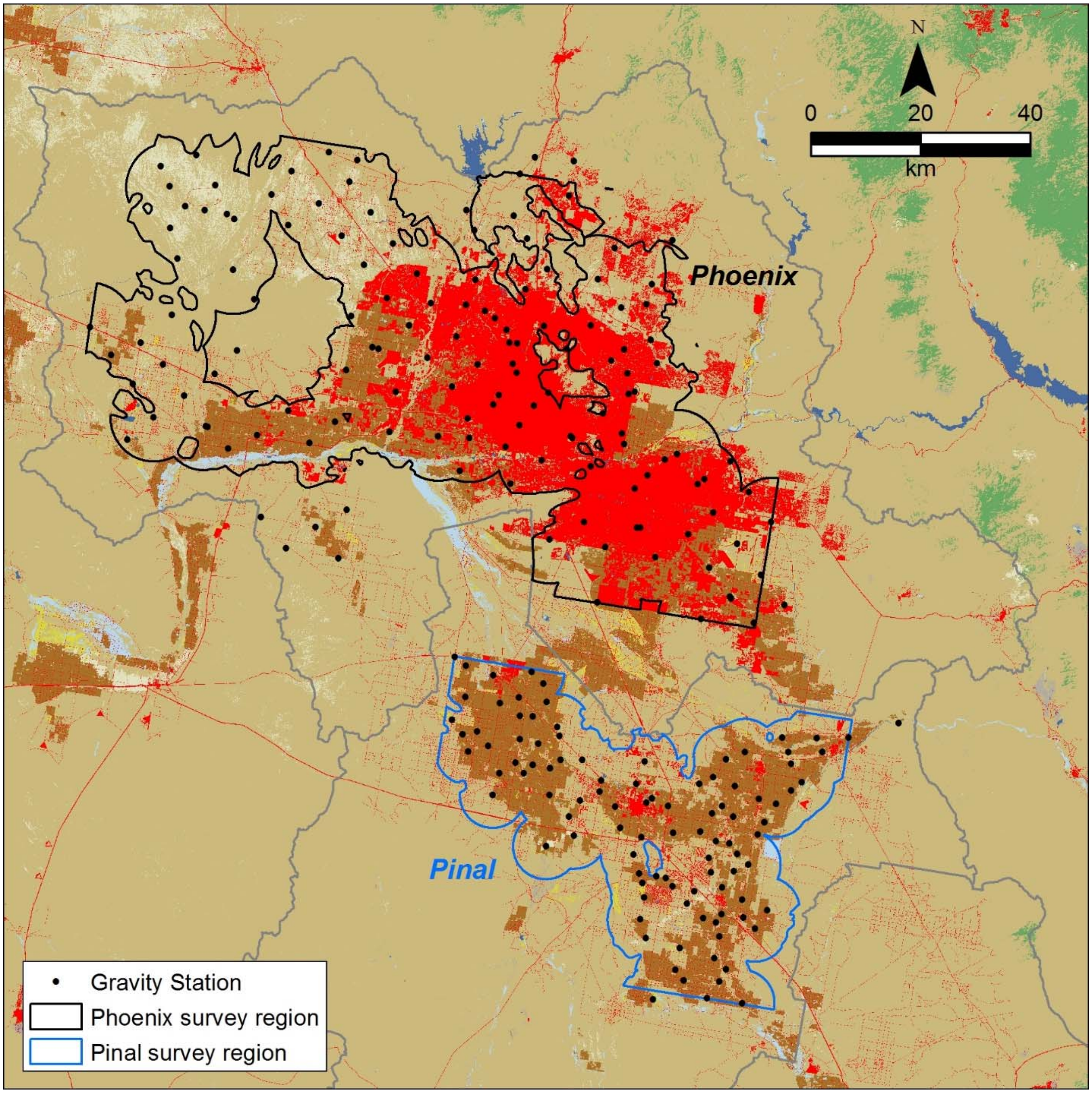

Figure S4. Distribution of ground-based gravity stations in the Phoenix and Pinal Active Management Areas. The background is land use showing the city of Phoenix in red. The polygon areas represent the survey analytical areas in the Phoenix AMA (5,625 km^2) and the Pinal AMA (2,543 km^2).

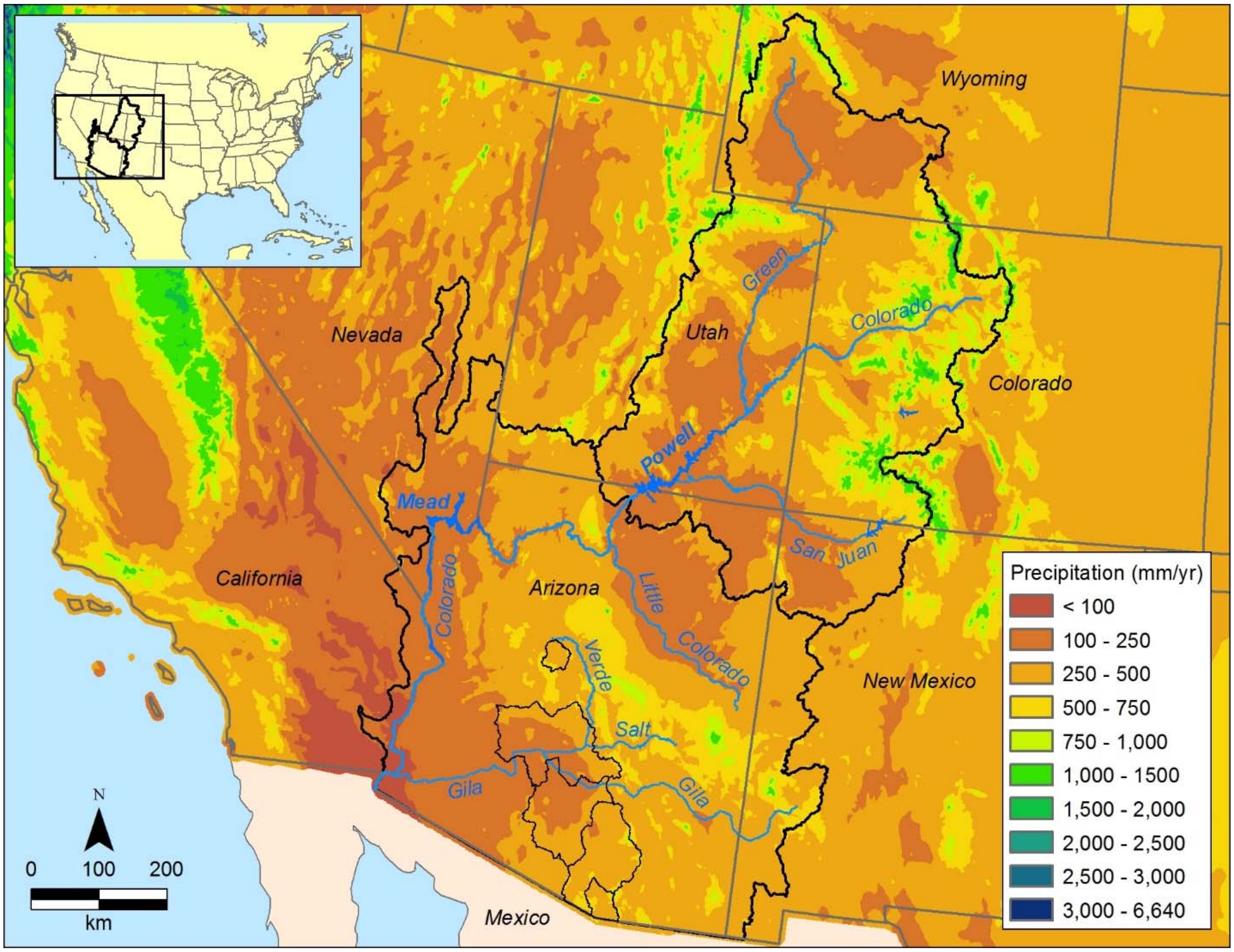

Figure S5. Distribution of mean annual precipitation based on data from PRISM (Precipitation-elevation Regressions on Independent Slopes Model, 1980 – 2014) (http://www.prism.oregonstate.edu/) in Colorado River Basin and surrounding regions. The Upper and Lower basins are outlined. The river system and major reservoirs are also shown along with the Arizona AMA boundaries.

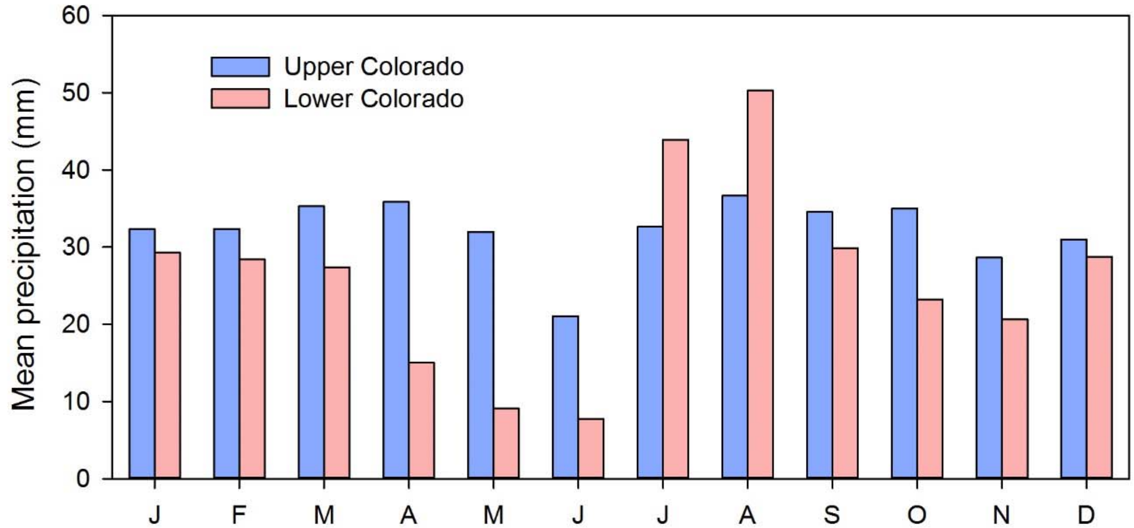

Figure S6. Monthly distribution of precipitation in the Upper and Lower Colorado River Basins based on PRISM monthly precipitation from 1981 to 2010 (http://www.prism.oregonstate.edu/).

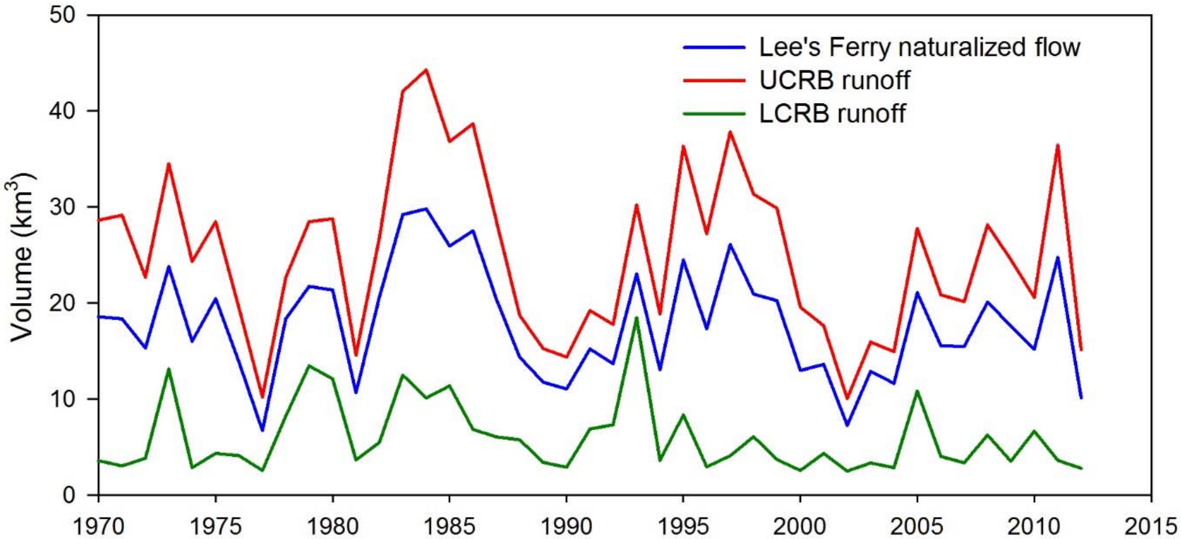

Figure S7. Comparison between runoff for the UCRB and LCRB based on USGS WaterWatch data and naturalized discharge for the Colorado River at Lee's Ferry, at the outlet of the UCRB (http://waterwatch.usgs.gov/).

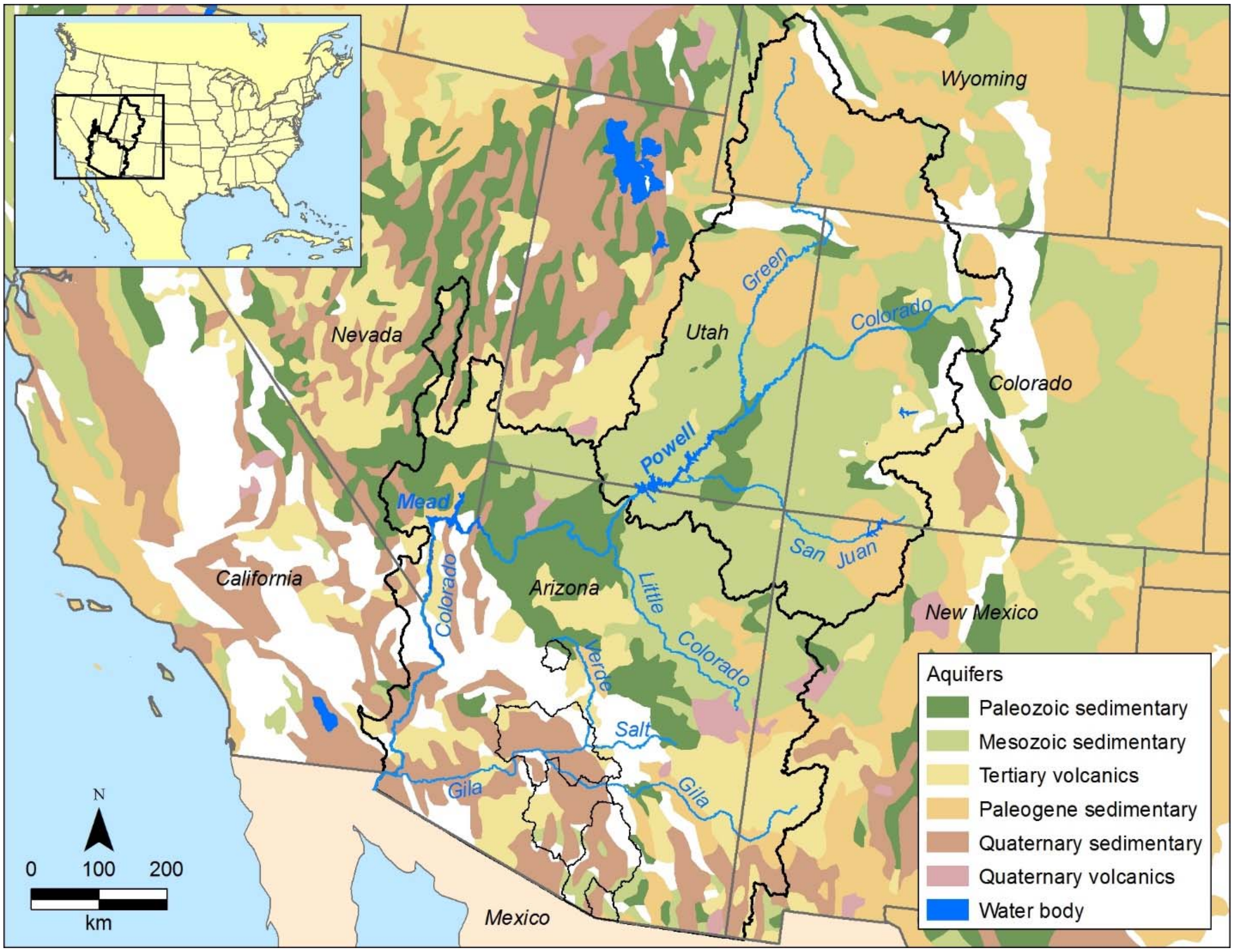

Figure S8. Distribution, general rock types, and geologic ages of aquifers in the Western US. Areas with no aquifer present are shown in white. The Upper and Lower Colorado River Basin boundaries are outlined. The river system and major reservoirs are also shown along with the Arizona AMA boundaries.

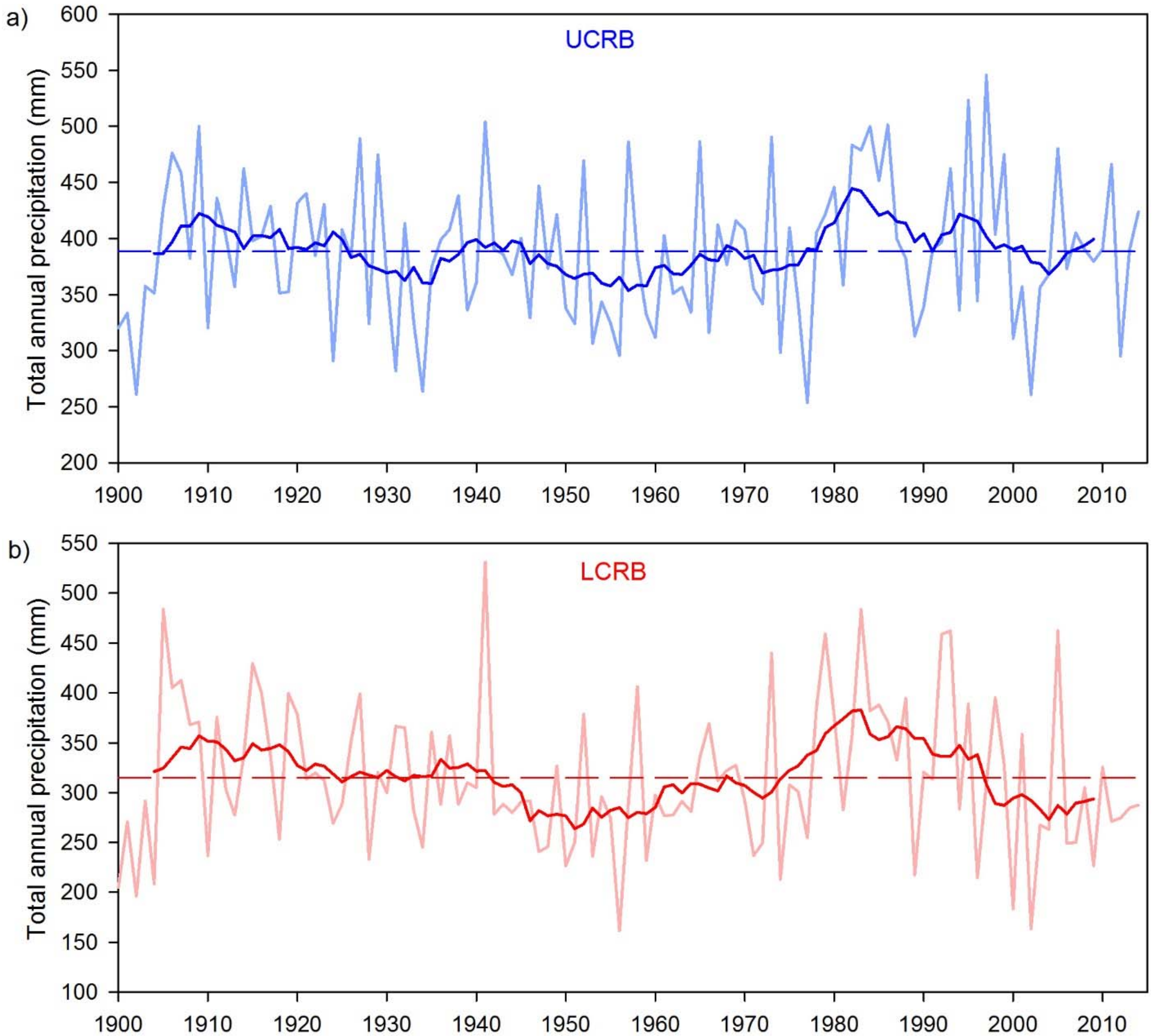

Figure S9. Total annual (water year) precipitation in the a) Upper (UCRB) and b) Lower (LCRB) Colorado River Basin based on PRISM data (Prism Climate Group, Oregon State University, http://www.prism.oregonstate.edu/) for the period 1900 – 2014. Dashed lines represent the period mean values of 389 mm (UCRB) and 315 mm (LCRB). Inter-annual variability, expressed as the coefficient of variability (CV), calculated as the standard deviation (SD) divided by the mean, is 16% in the UCRB (SD=63 mm) and 23% in the LCRB (SD=72 mm). Heavy solid lines represent centered 10-yr moving averages, ranging from 354 to 445 mm (UCRB) and 264 to 383 mm (LCRB).

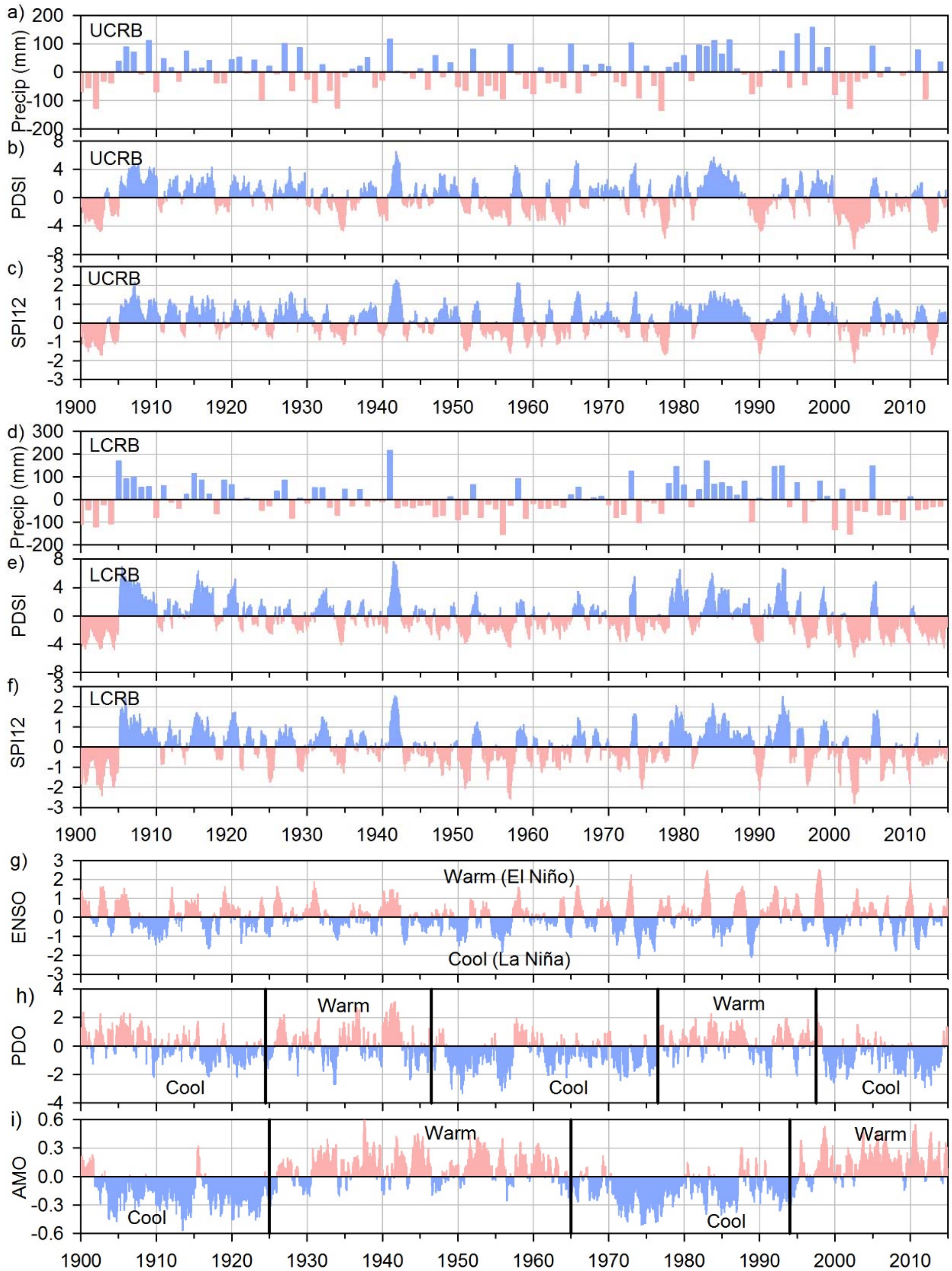

Figure S10. Annual precipitation, Palmer drought severity index (PDSI), and 12-month moving average Standard Precipitation Index (SPI12) for the (a, b, c) Upper (UCRB) and (d, e, f) Lower (LCRB) Colorado River Basin regions. Also shown are global values for g) the El Niño Southern Oscillation (ENSO), h) the Pacific Decadal Oscillation (PDO), and i) the Atlantic Multidecadal Oscillation (AMO). All values are expressed as anomalies relative to the period average. (http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php)

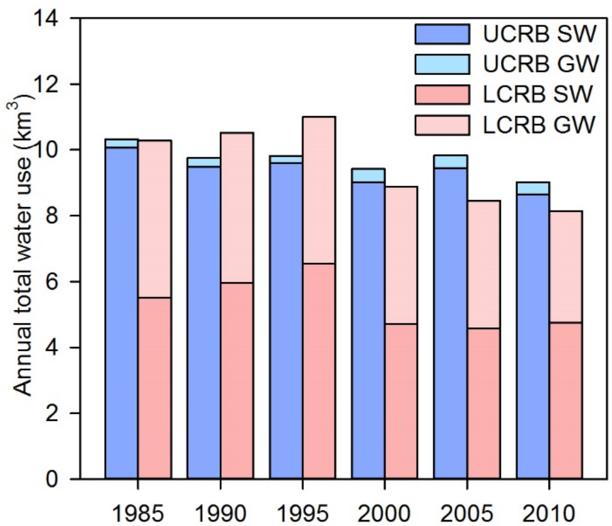

Figure S11. Annual total surface water (SW) and groundwater (GW) withdrawals in the Upper (UCRB) and Lower (LCRB) Colorado River Basin regions based on USGS County Water Use reports published at 5-year intervals beginning in 1985 (http://water.usgs.gov/watuse/data/index.html). Data were proportionally adjusted for land use areas and county percentages that overlap basin boundaries.

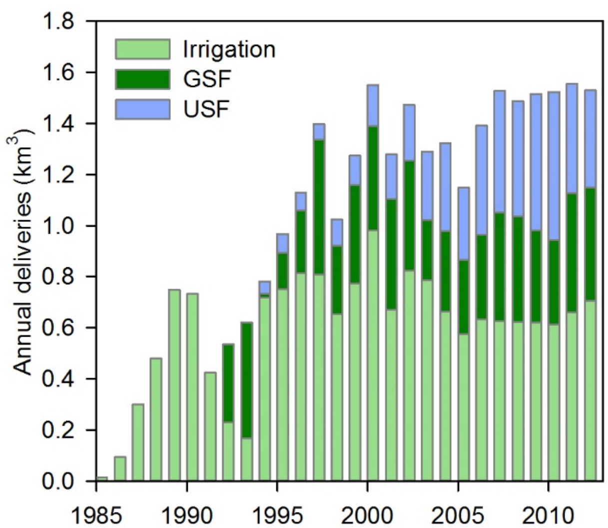

Figure S12. Annual deliveries from the Colorado River through the Central Arizona Project (CAP) aqueduct to Phoenix, Pinal, and Tucson AMAs, showing water deliveries to irrigation, groundwater savings facilities (in lieu recharge where former groundwater discharge switches to surface water), and underground storage facilities (managed aquifer recharge through spreading basins).

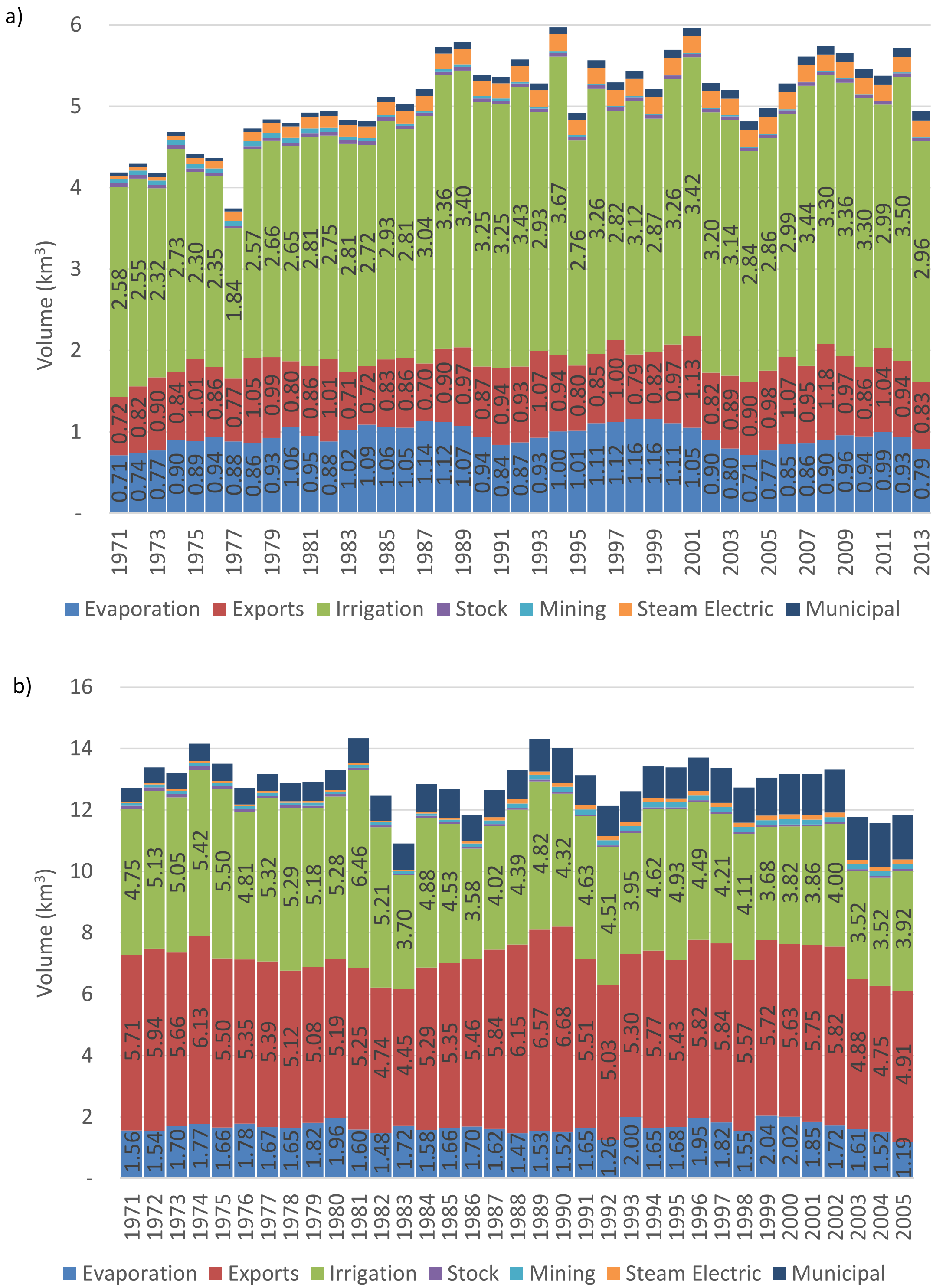

Figure S13. Time series of water consumption based on USBR Consumptive Uses and Losses (CUL) reports for a) the UCRB and b) the LCRB and shown in Table S8. CUL reports are not available for the LCRB after 2005. (http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html)

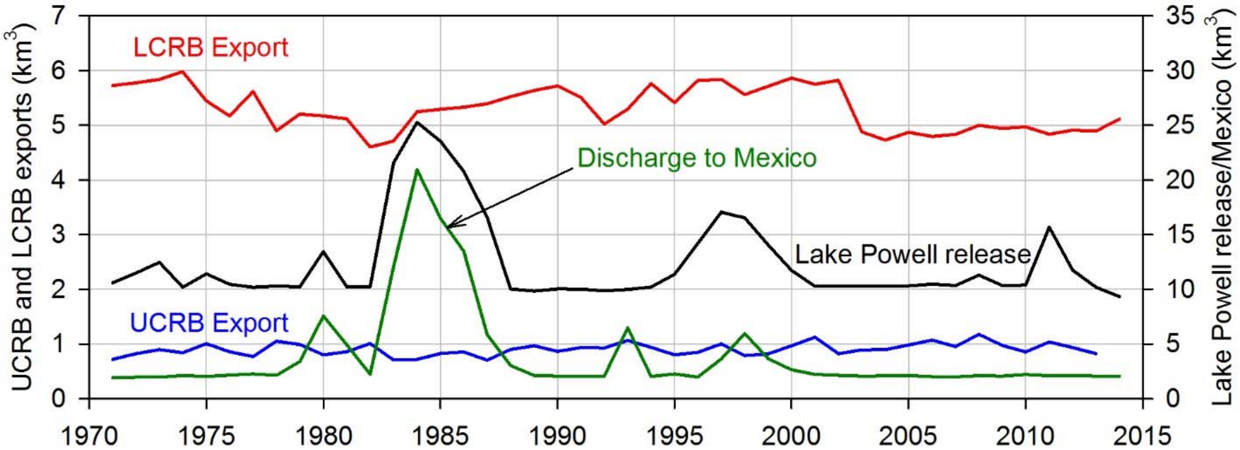

Figure S14. Annual exports from the Upper (UCRB) and Lower (LCRB) Colorado River Basin to neighboring basins in Colorado, Utah, New Mexico, and California, compared with total annual releases from Lake Powell (estimated as discharge at Lee's Ferry), and total annual discharge to Mexico. Total annual exports averaged 6.2 km^3 during 1971-2012 (range 5.4 – 6.9 km^3). Annual discharge at Lee's Ferry downstream from Lake Powell is generally ~10 km^3 during normal and dry years, increasing during wet periods to as high as 25 km^3 during 1984. Similarly, discharge to Mexico is generally 2.2 km^3 during normal and dry years, increasing during wet periods to as high as 21 km^3 during 1984.
(http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html)

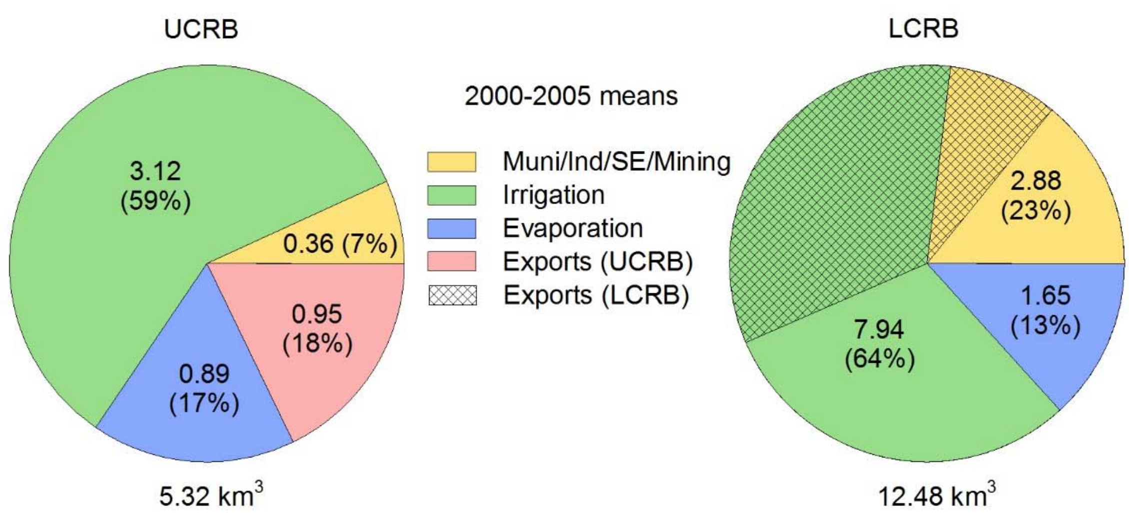

Figure S15. Mean annual total water consumption by use category for the period 2000-2005 in the Upper (UCRB) and Lower (LCRB) Colorado River Basin based on USBR CUL reports. Exports from the UCRB are not apportioned by end use due to lack of data. Exports from the LCRB represent a mean annual total of 5.29 km^3, equivalent to total consumption in the UCRB, and include 4.17 km^3 (79%) for irrigation and 1.12 km^3 (21%) for combined municipal (Muni), industrial (Ind), steam electric power generation (SE) and mining uses. Exports to Mexico are not included.
(http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html)

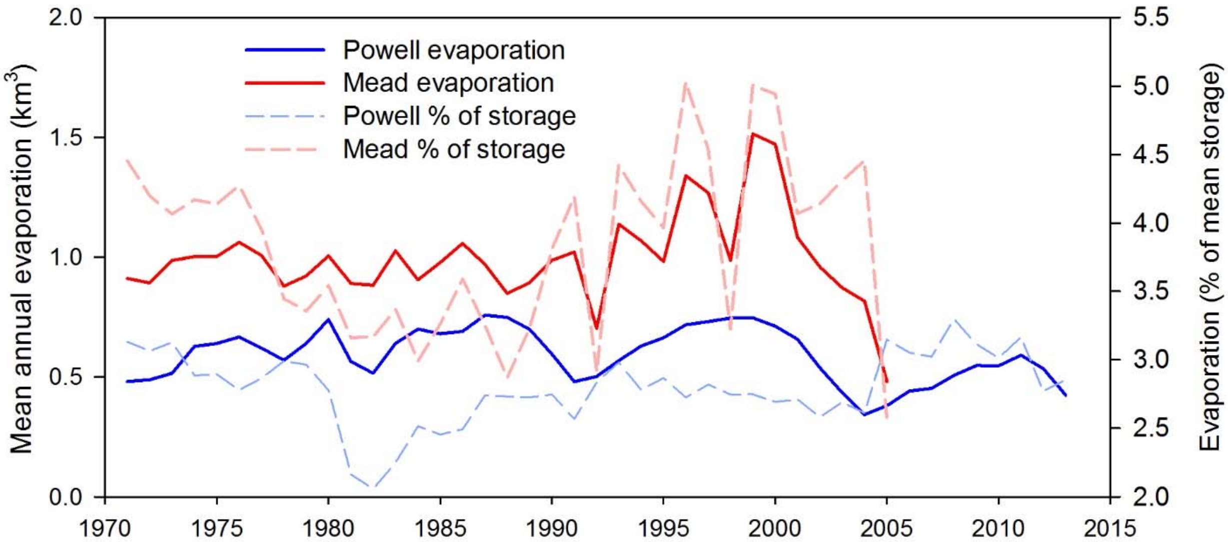

Figure S16. Mean annual evaporative losses from Lake Powell and Lake Mead, expressed both as volumes and as respective percentages of total (actual) storage for each reservoir. (http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html)

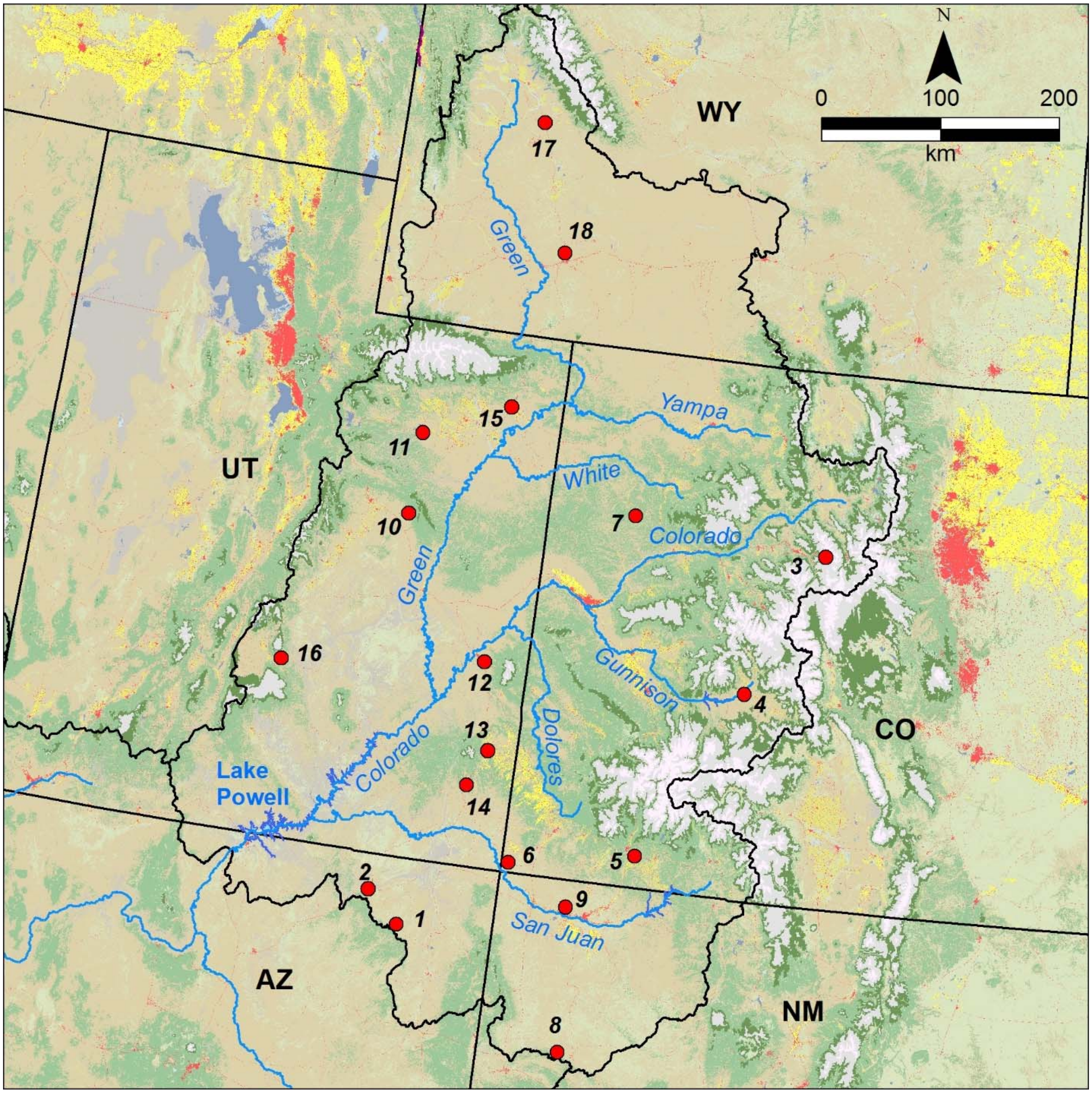

Figure S17. Locations of groundwater well hydrographs shown in Figure S18 and listed in Table S10. (http://waterdata.usgs.gov/nwis)

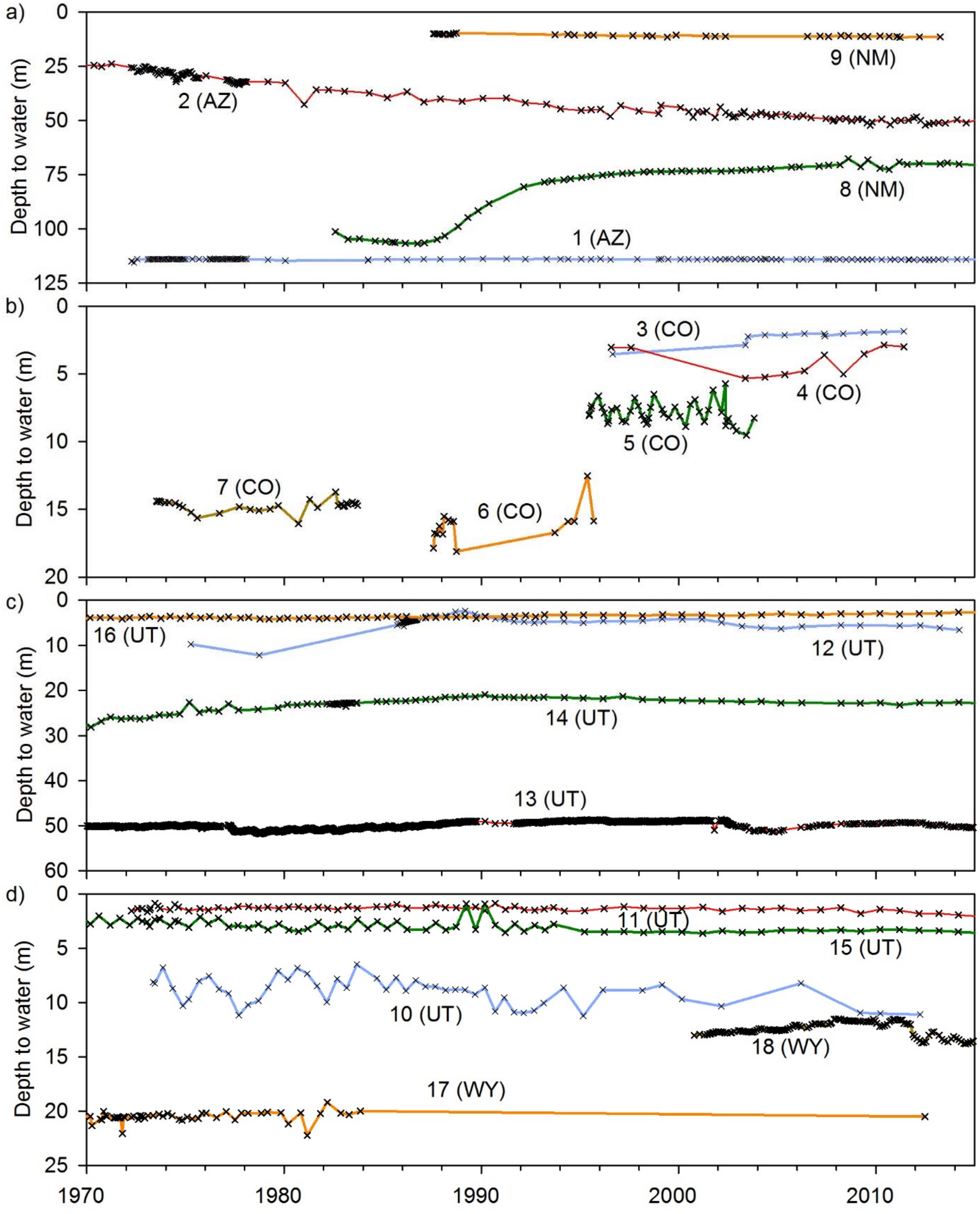

Figure S18. Groundwater hydrographs for wells at locations shown in Figure S17. Hydrographs are labeled with the map reference number and the state abbreviation in parenthesis. (http://waterdata.usgs.gov/nwis)

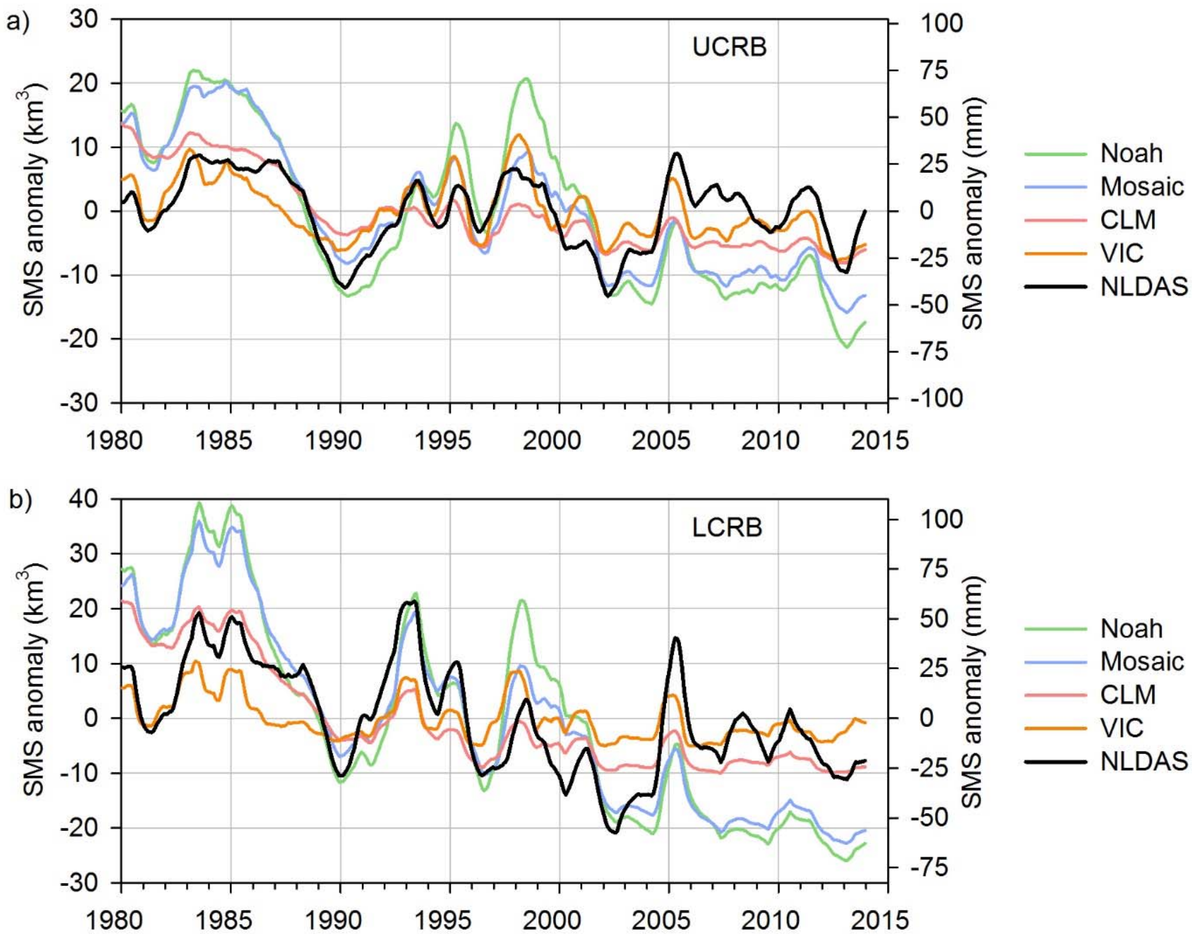

Figure S19. Time series for the a) Upper (UCRB) and b) Lower (LCRB) Colorado River Basin of GLDAS soil moisture storage based on the Noah, Mosaic, CLM, and VIC models. The composite average of the corresponding NLDAS soil moisture storage models is also shown. Values shown represent the 12-month moving average anomaly for the period shown.

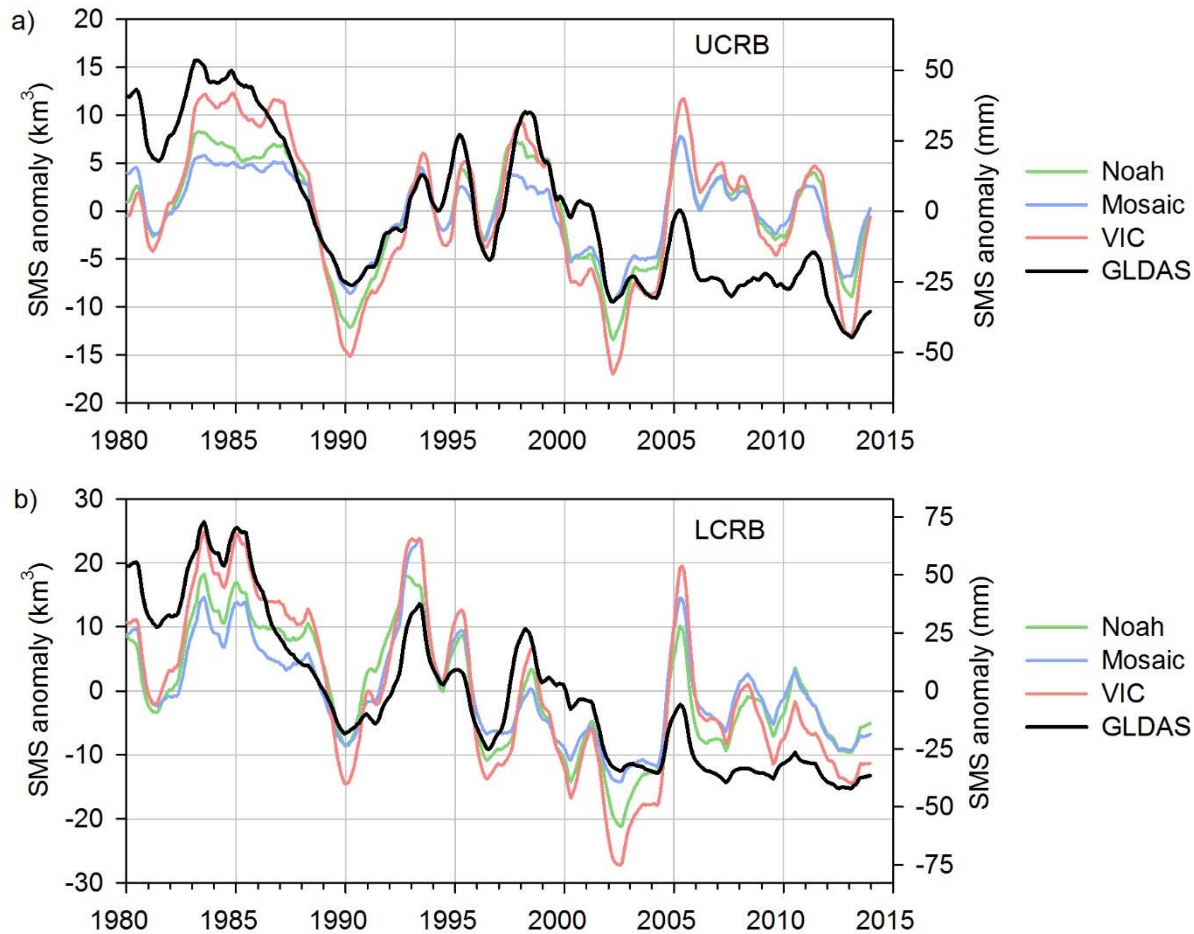

Figure S20. Time series for the a) Upper (UCRB) and b) Lower (LCRB) Colorado River Basin of NLDAS soil moisture based on the Noah, Mosaic, and VIC models. The composite average of the corresponding GLDAS soil moisture models is also shown. Values shown represent the 12-month moving average anomaly for the period shown.

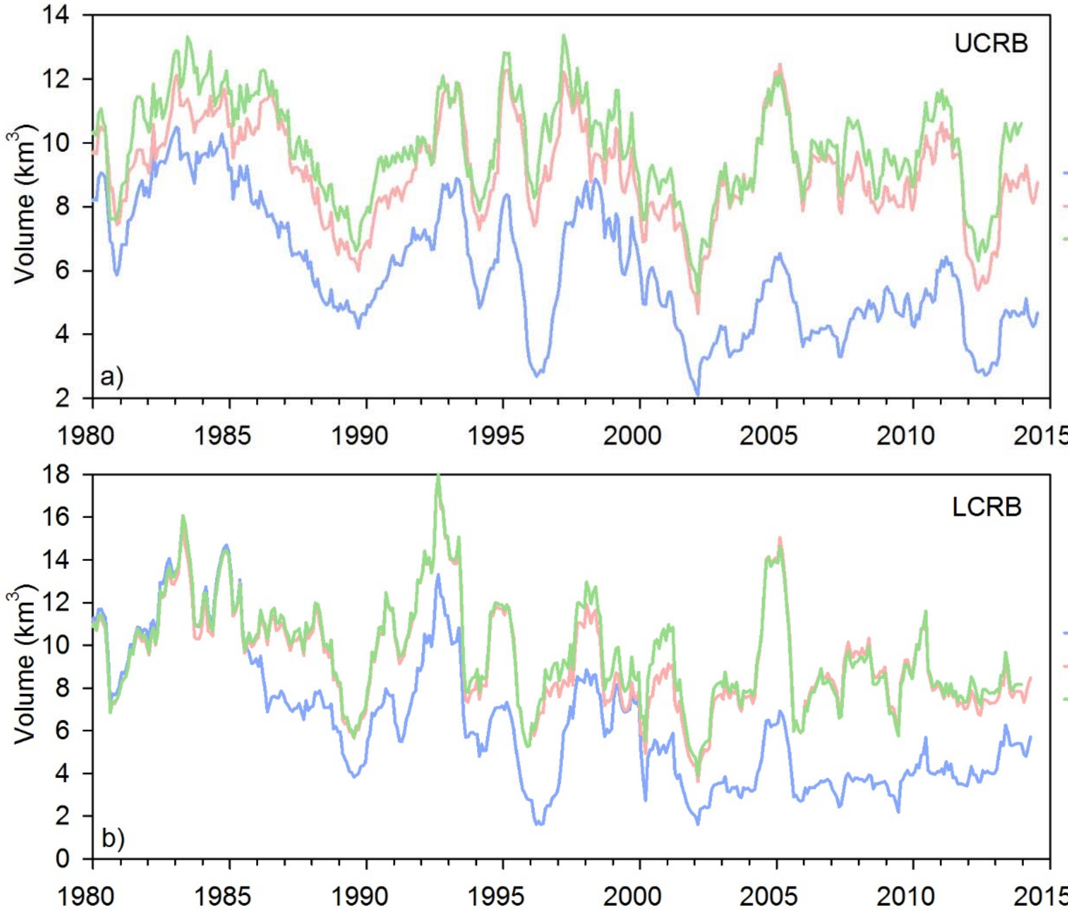

Figure S21. Comparison between precipitation inputs to the GLDAS and NLDAS land surface models with that from PRISM (http://www.prism.oregonstate.edu/) in the a) Upper (UCRB) and b) Lower (LCRB) Colorado River Basin regions. Values represent the 12-month moving average of total annual precipitation.

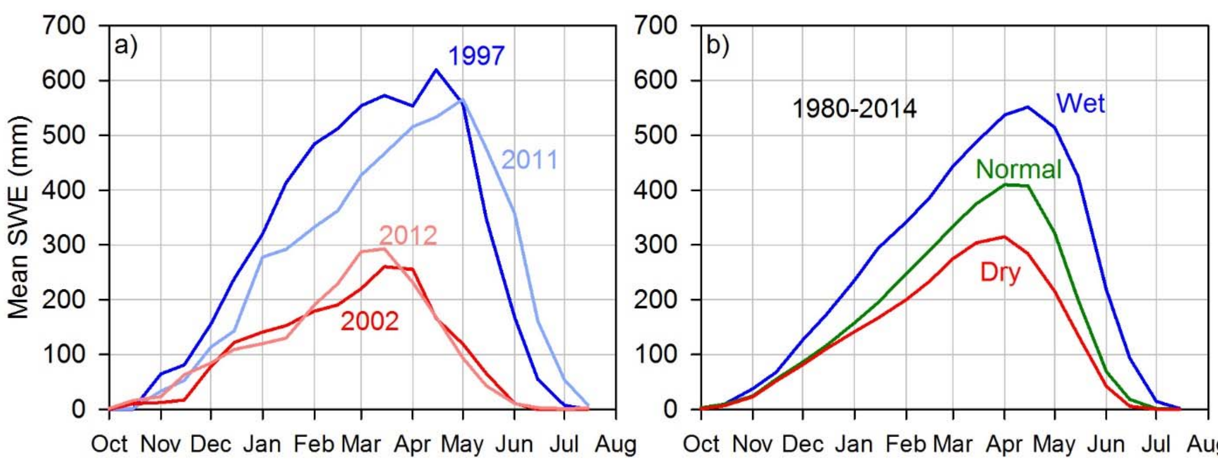

Figure S22. Temporal development and magnitude of snow water equivalent (SWE) for a) representative wet and dry years and b) the means of the wettest third, middle (normal) third and driest third of years during the period 1980-2014 in the Upper Colorado River Basin. (http://www.wcc.nrcs.usda.gov/snow/)

Section 3: Composite Groundwater Storage Hydrograph

Composite groundwater-level hydrographs were developed for the LCRB and include (a) minimally developed regions, (b) intensively developed regions used for irrigated agriculture outside of Colorado River CAP deliveries, (c) intensively developed regions that receive Colorado River through the CAP aqueduct (Active Management Areas), and (d) Colorado River mainstem region (Fig. S23). Area d was neglected because irrigation is derived directly from the Colorado River and should have minimal GWS changes. Areas of widespread confined aquifers were excluded because of limited GRACE derived GWS change related to low storage coefficients.

The following procedure was used to develop composite groundwater-level hydrographs in the LCRB.

1. Isolated Nov-March groundwater level observations
2. Removed groundwater levels flagged for issues such as pumping wells, no observations, and obvious data entry errors
3. Calculated average groundwater level for each region and anomaly based on the mean for the period of analysis, 1980-2015
4. Converted GW level changes to GWS changes by multiplying by a specific yield of 0.10
5. Removed years with fewer observations
6. Calculated mean anomaly for each year
7. Area weighted GW level and GWS changes based on aquifer area for different regions

During data processing the following issues were identified. The number of observations were variable for each year which were attributed to several causes, 1. change in data agency from USGS to Arizona Dept. of Water Resources (ADWR) in the mid-1980's, 2. occasional detailed data collection in specific areas by ADWR, 3. a partial water level record for 2015, and 4. as yet unavailable observations from Tucson Water agency after 2012. There are also occasional years with fewer observations during 1990, 93, and 96.

A specific yield of 0.10 was used, which is consistent with values applied to the upper layers in groundwater flow models across most of Arizona..

An average groundwater level anomaly was produced for each Active Management Area. The WL anomaly plot is representative of the Tucson AMA. Recovery after 2004 is likely due to importation of Colorado River water through the CAP aqueduct, artificial recharge of CAP water, and retirement of many production wells. The trend is delayed from the recovery trend in Pinal AMA because of the later completion of the CAP and subsequent deliveries to the Tucson area.

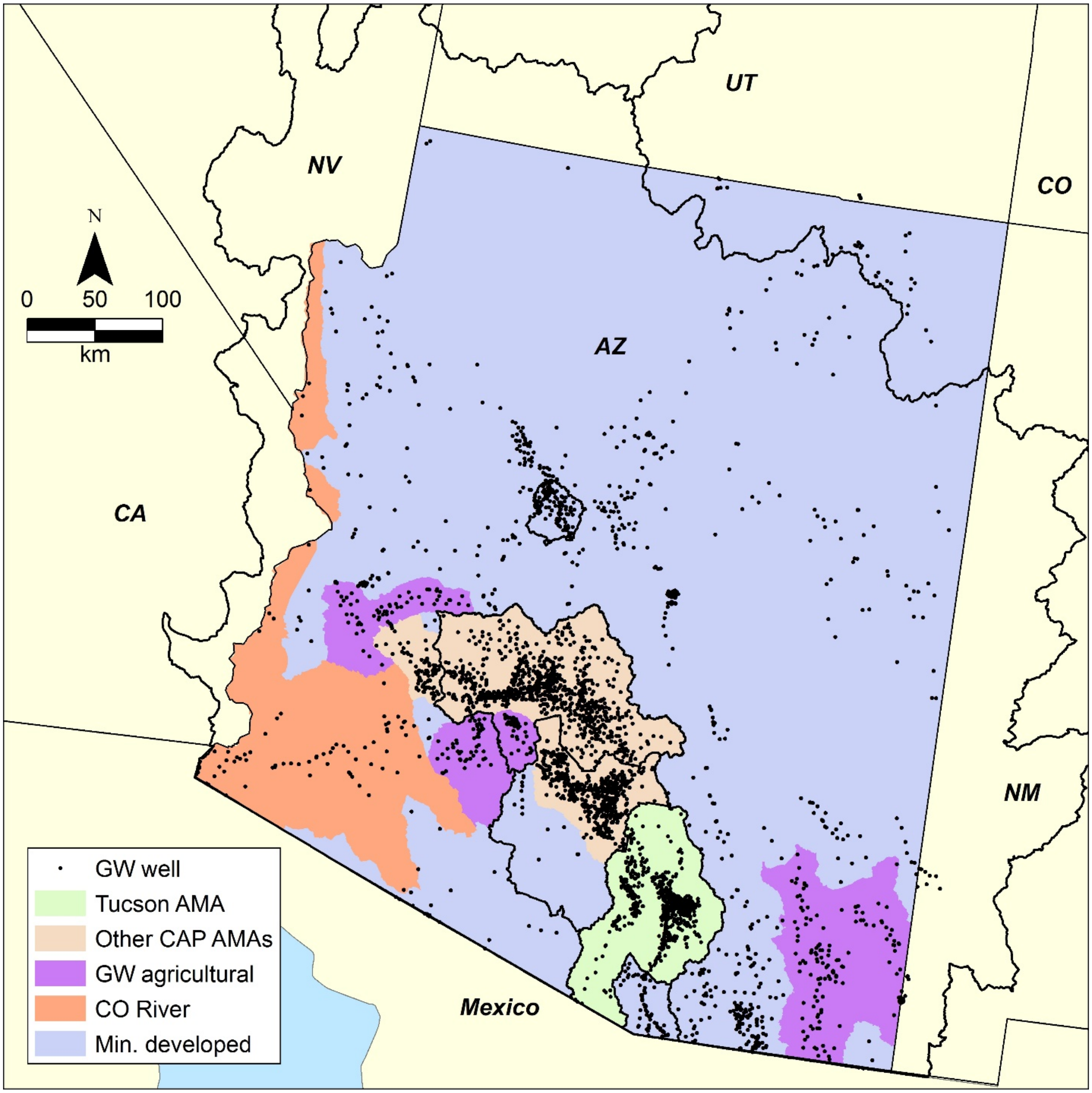

Figure S23. Location of groundwater wells used to develop the groundwater-level anomaly. Tucson AMA is shown separately because of the large number of monitoring wells. Wells along the Colorado River (and lower Gila) were excluded in the hydrographs because they are dominated by irrigation from the river. Composite hydrographs for different regions are shown in Figs. 5 and S24.

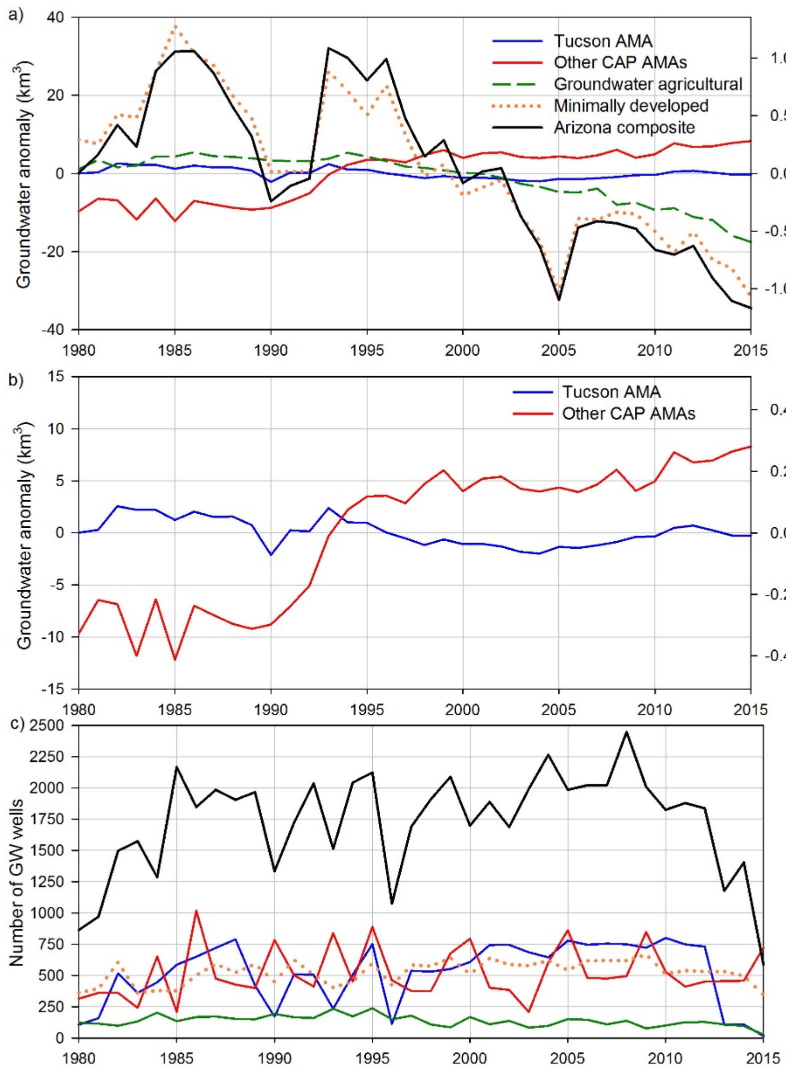

Figure S24. Groundwater storage changes for a) all analyzed regions of Arizona and b) the active management areas (AMAs), and c) the corresponding numbers of groundwater wells used in the analyses. The right-hand axes show the equivalent depths of water relative to the State of Arizona area, which closely approximates the LCRB region. The Phoenix, Pinal, and Tucson AMAs receive water from the Colorado River through the Central Arizona Project (CAP), groundwater agricultural areas include regions outside areas of CAP deliveries, and minimally developed regions represent areas outside the AMAs and intensive irrigation regions. The Phoenix and Pinal AMA regions were combined to form the "Other CAP AMA" values shown. Regional groundwater storage volume changes were estimated using the mean observed water level changes for unconfined aquifer areas (i.e., excluding confined aquifer areas in each region) multiplied by a uniform specific yield value of 0.10. The regional values were then summed to obtain the Arizona composite value shown. The composite thus represents an area-weighted average of all regions (Tucson AMA: 3% of area, Phoenix and Pinal AMA: 7%, GW agricultural: 7%, minimally developed regions: 75%). The remaining 8% represents areas adjacent to the Colorado River and Gila River controlled by river water irrigation that do not undergo significant storage changes. Note low number of well observations in recent years, reducing the reliability of recent GWS changes.

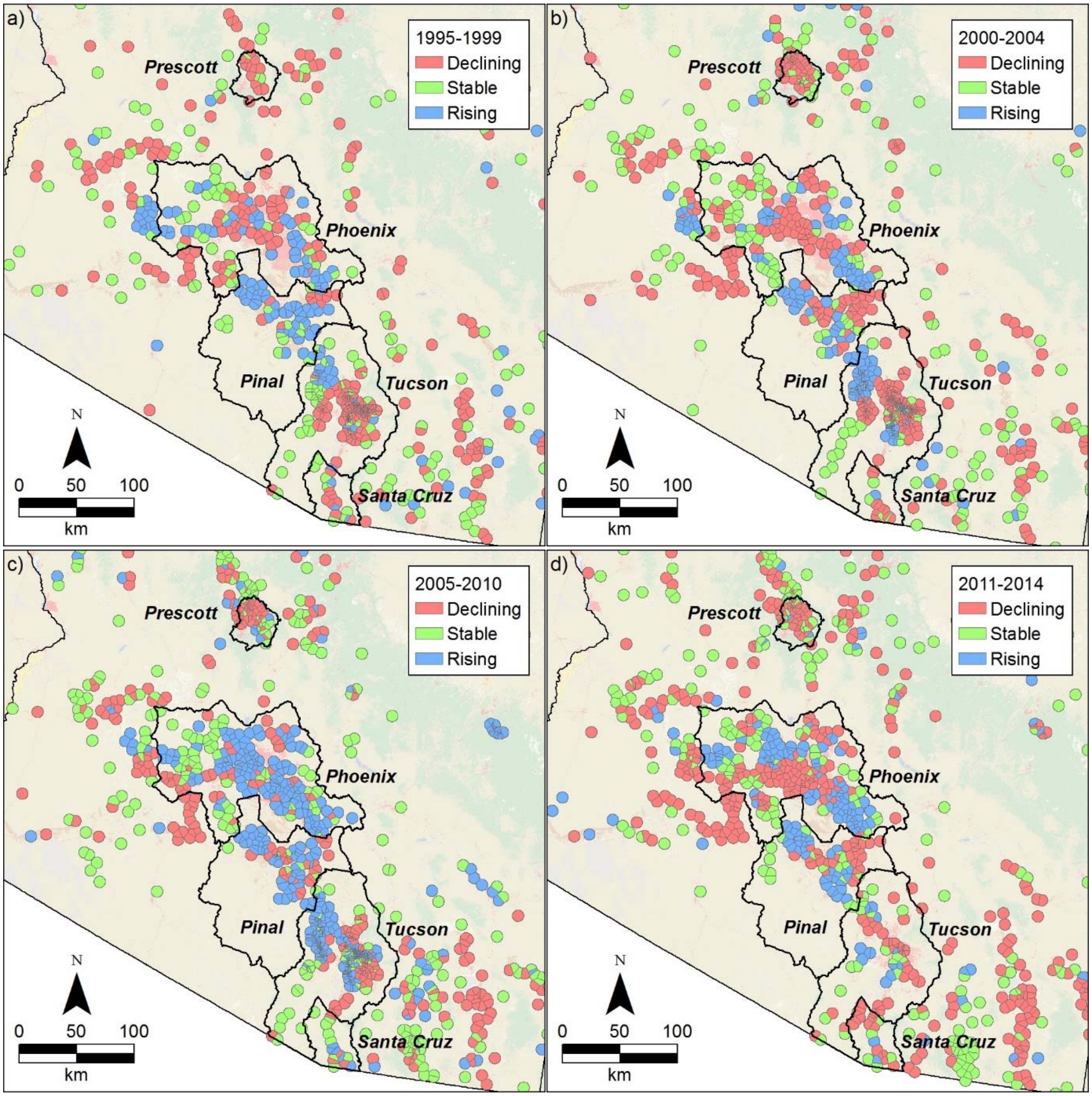

Figure S25. Trends in groundwater levels over five year periods using the same approach as described in Tillman and Leake (2010). Percent wells showing increasing, stable, and decreasing trends are shown in Table S11.

Section 4: Processing and Uncertainties in GRACE Data

A variety of sources and approaches are available for processing GRACE data. The three primary processing centers that provide GRACE data include The University of Texas Center for Space Research (CSR,http://www.csr.utexas.edu/grace/), NASA Jet Propulsion Lab (JPL, http://grace.jpl.nasa.gov/mission/grace/) and the German Research Centre for Geosciences (GFZ, http://www.gfz-potsdam.de/grace/). The most recent GRACE data include release 5 (RL05). Most studies that used GRACE data in the past relied on Spherical Harmonics (SH) data. Processing GRACE data was generally conducted at a basin scale and generally involved truncation at 60°, destriping to remove north south bands (Swenson and Wahr, 2006), and filtering to remove high frequency noise, commonly Gaussian filters at 350 km (e.g. Rodell et al., 2009). Because of signal loss during truncation and filtering, most studies apply the same processing (truncation and filtering) to global models such as the Global Land Data Assimilation System (GLDAS) land surface models (LSMs) and determine a scaling factor from comparison of truncated and filtered model output versus the original model output. Such scaling factors are applied to GRACE data to restore signal loss.

More recently, Landerer and Swenson (2012) provided a gridded GRACE product based on SH analysis to increase use of GRACE data by hydrologists. The GRACE TELLUS website, supported by NASA JPL (http://grace.jpl.nasa.gov/), provides gridded GRACE data at 1 degree plus scaling factors based on original CSR, JPL, or GFZ data.

Mass concentration (Mascons) parameters provide an alternative processing approach to Stokes coefficient parameters used in spherical harmonics solutions (Rowland et al., 2010; Save et al., 2015; Watkins et al., 2015). While the spherical harmonic approach involves computation of the gravitational potential of the entire mass anomaly over the globe, the Mascons approach can treat anomalies as point masses or tiles, ranging from 1 to 4 degree grids. We need to determine the mass anomaly for each tile that represents the signal in space. The GRACE K band range rate data are inverted to estimate the mass anomaly for each tile. Mass is represented as an equivalent water height (EWH). The KB range rate data represent the primary measurements that are inverted to gravity. Because the inversion process is nonunique, constraints are generally applied. The Mascons solutions developed by Save et al. (2015) applies constraints based on regularized GRACE spherical harmonic solutions. This approach localizes the signal and reduces leakage. Regularization dampens all errors. Solutions based on regularized GRACE spherical harmonic solutions (Save et al., 2012) are fitted to KBRR data to ensure that all the signal observed by the satellites is captured in the solution. Most GRACE processing approaches do not compare the solutions to the original KBRR data to test for signal losses. Applying constraints during processing is much better than post-solution constraints applied in typical SH processing that then requires signal restoration.

The Mascon solutions used in this study were produced by CSR (Save et al., 2015). These solutions offer several advantages over traditional SH processing approaches: processing to 120 degree increases spatial resolution, 1 degree grids represent much higher resolution that previous mascon approaches (2 – 4 degree grids), and time variable constraints to balance signal and noise whereas most studies use a fixed constraint in time independent of signal or error magnitudes. While the more detailed analyses provided by this mascon processing is computationally intensive, Tikhonov regularization and massive computing power at Texas Advanced Computing Center (TACC) were used to provide the solutions. The results should represent much higher spatial resolution time variable gravity output that is based entirely on GRACE data and does not rely on external land surface models and does not require any signal restoration.

Trends in TWS or TWSe and water budget components were determined by removing seasonal signals (annual and semi-annual) using unweighted least squares fit, then a linear regression was conducted to derive slope rates during a given time span or drought event, and also Mann-Kendall tests and 95% significant level tests were performed.

GRACE SH solutions (gridded SH using CSR, GFZ, and JPL raw data and basin scale output using CSR raw data) are generally rescaled to restore any signal loss during processing. Scaling factors are generally estimated by applying GRACE processing to LSMs. We applied GRACE processing (truncation and filtering) to simulated TWS using WorldGap Global Hydrologic Model (WGHM) and NLDAS soil moisture storage and compared these data with the raw data to estimate the scaling factors. Differences in water storage before and after filtering are low to moderate (Figs. S29, S30); therefore, we did not rescale the TWS data for the SH processing because we thought more error might be introduced through rescaling.

Uncertainties in GRACE Data

Various approaches have been adopted to estimate uncertainties in water storage changes from GRACE data. In this study we evaluated differences in TWS from different processing approaches as an estimate of the uncertainties in GRACE TWS. TWS changes were estimated using CSR Mascons, GRACE SH output from Tellus CSR, JPL, and GFZ gridded data, and basin scale output using CSR data. TWS depletions during the recent drought from the different outputs are provided in Table S12 and variability among the different outputs provides an estimate of GRACE TWS uncertainty. GWS changes are also estimated from GRACE TWS as a residual after subtracting changes in SnWS, RESS, and SMS from TWS. A wide range in SMS from GLDAS and NLDAS SMS were considered when estimating GWS from GRACE TWS and provides an estimate of GWS uncertainties. We calculated bounding estimates of GWS using a high value of TWS from GRACE and low estimate of SMS from one of the LSMs to estimate an upper bound on GWS and vice versa to estimate an upper bound on GWS.

Uncertainties in time series data are often evaluated using linear regression. However, this source of uncertainty is generally much lower than the variability among different produces as discussed in the previous paragraph.

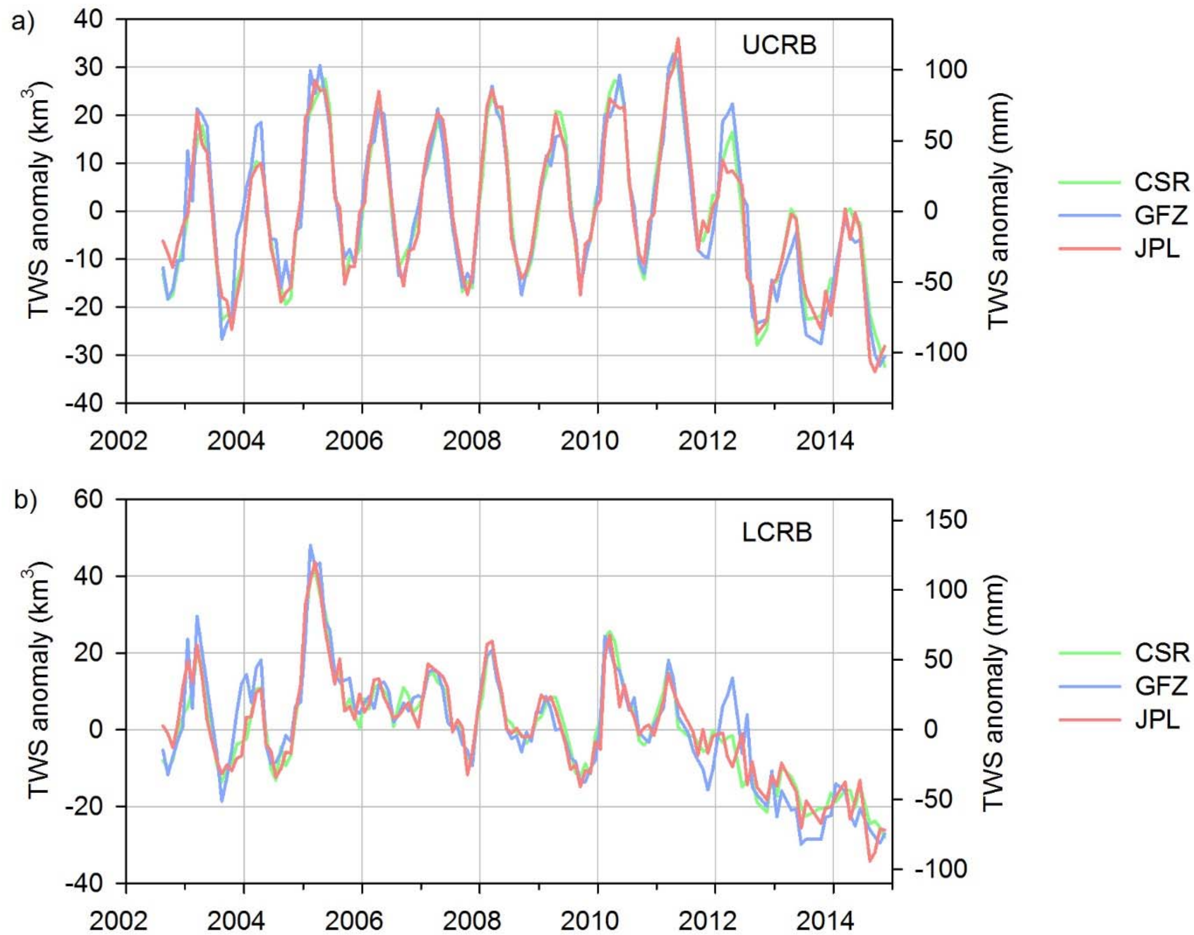

Figure S26. Comparison between GRACE TWS anomalies based on GRACE gridded data provided by JPL Tellus (http://grace.jpl.nasa.gov/) using CSR, GFZ, and JPL raw data for a) the Upper (UCRB) and b) the Lower (LCRB) Colorado River Basin regions.

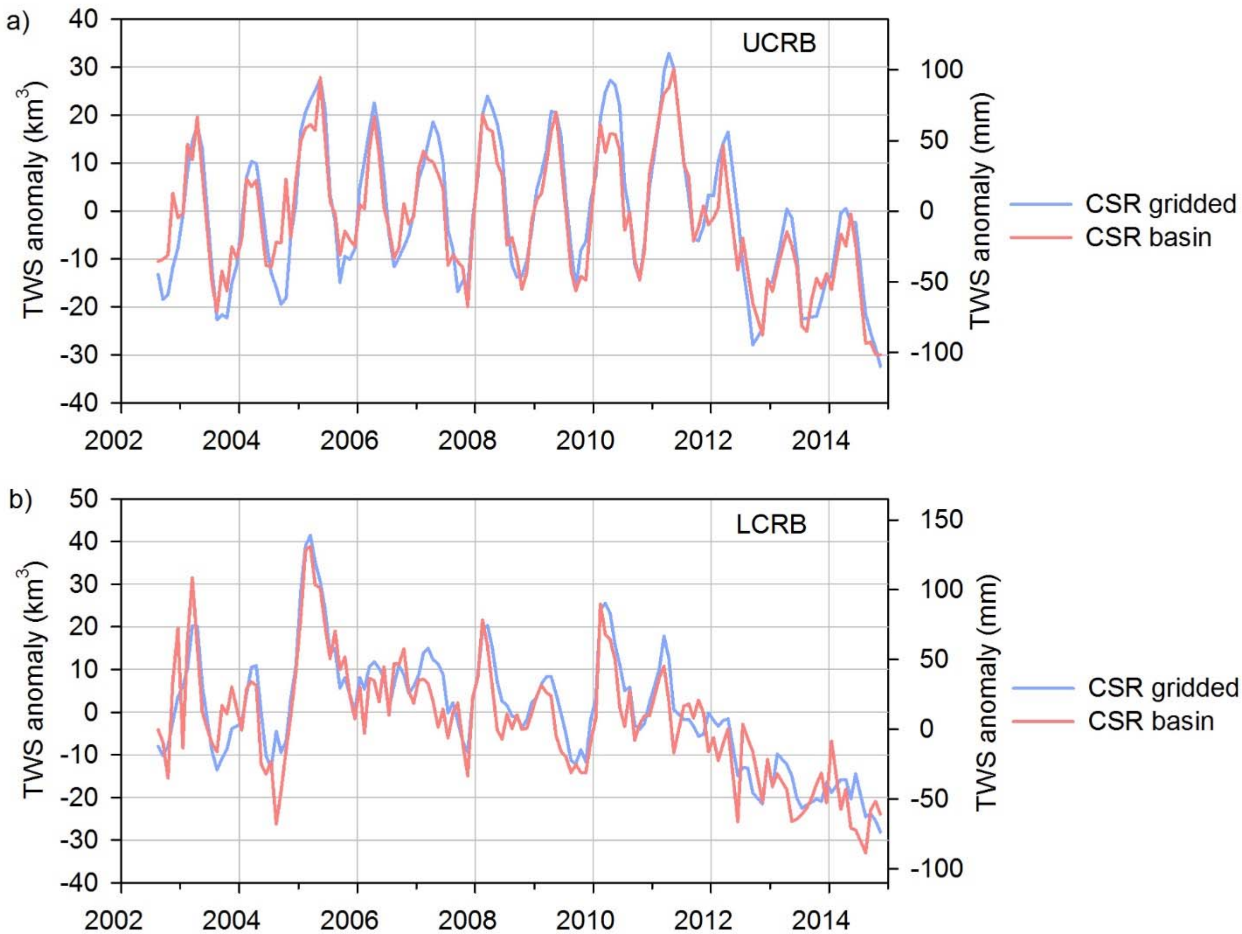

Figure S27. Comparison between GRACE TWS anomalies based on the JPL Tellus gridded data based on CSR (http://grace.jpl.nasa.gov/) and CSR basin models for the a) Upper (UCRB) and b) Lower (LCRB) Colorado River Basin regions.

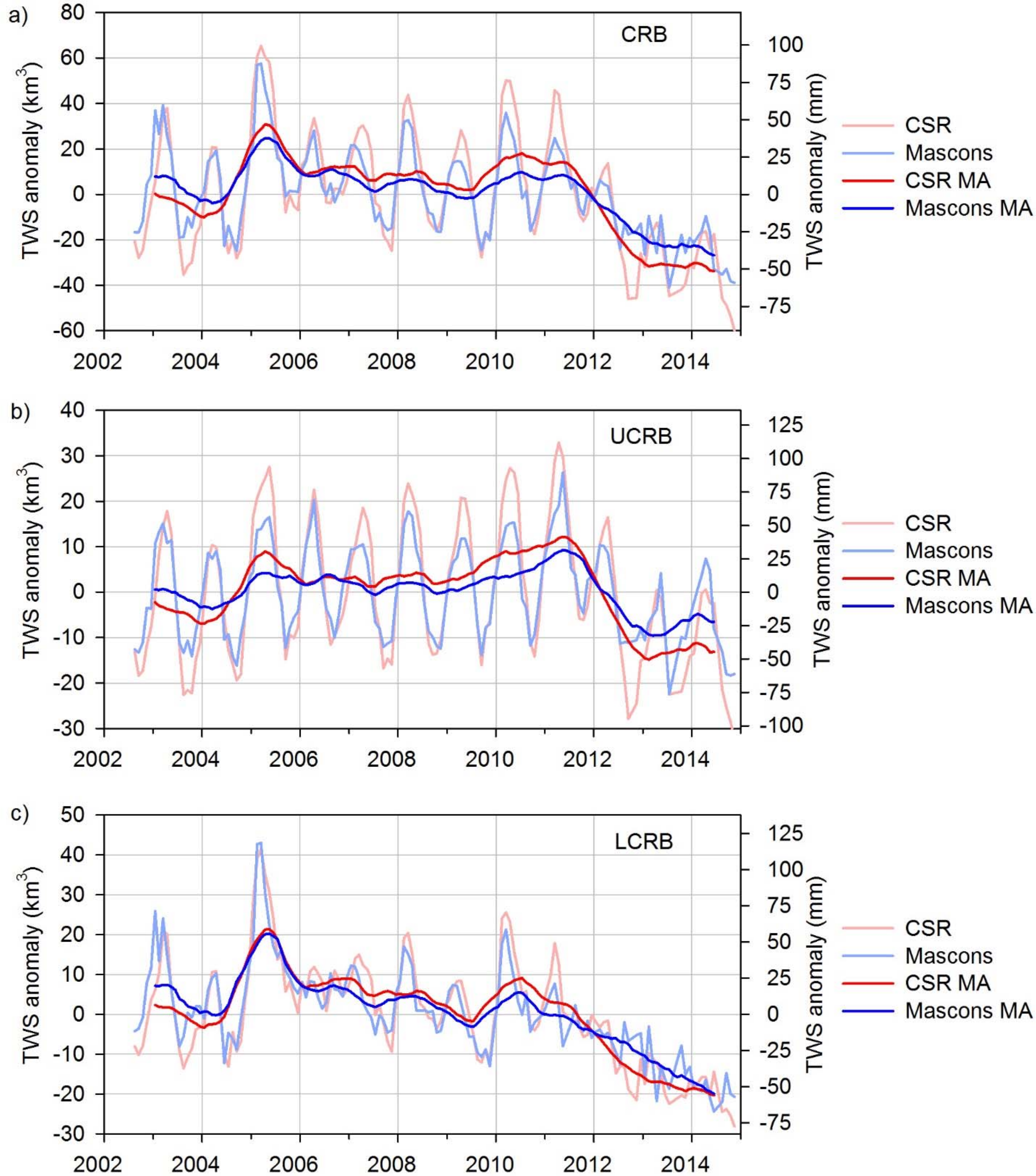

Figure S28. Comparison between GRACE TWS anomalies based on the gridded data using CSR raw data provided by JPL TELLUS (http://grace.jpl.nasa.gov/) and Mascons data provided by CSR for the a) entire Colorado River Basin, b) the Upper, and c) the Lower (LCRB) basin regions. Monthly values and 12-month moving average (MA) values are shown.

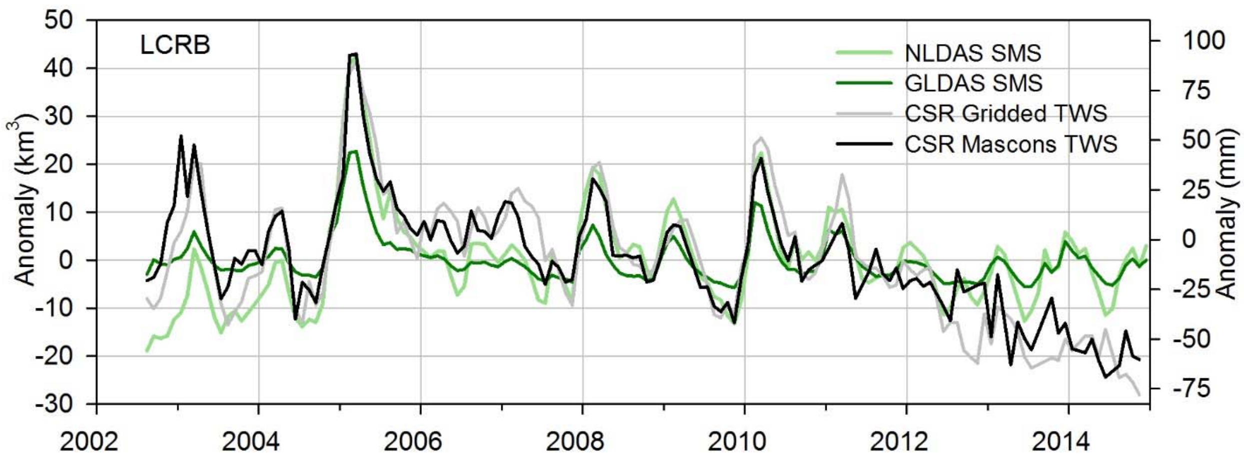

Figure S29. Comparison between different GRACE TWS anomalies and SMS anomalies determined using the NLDAS and GLDAS models for the LCRB region.

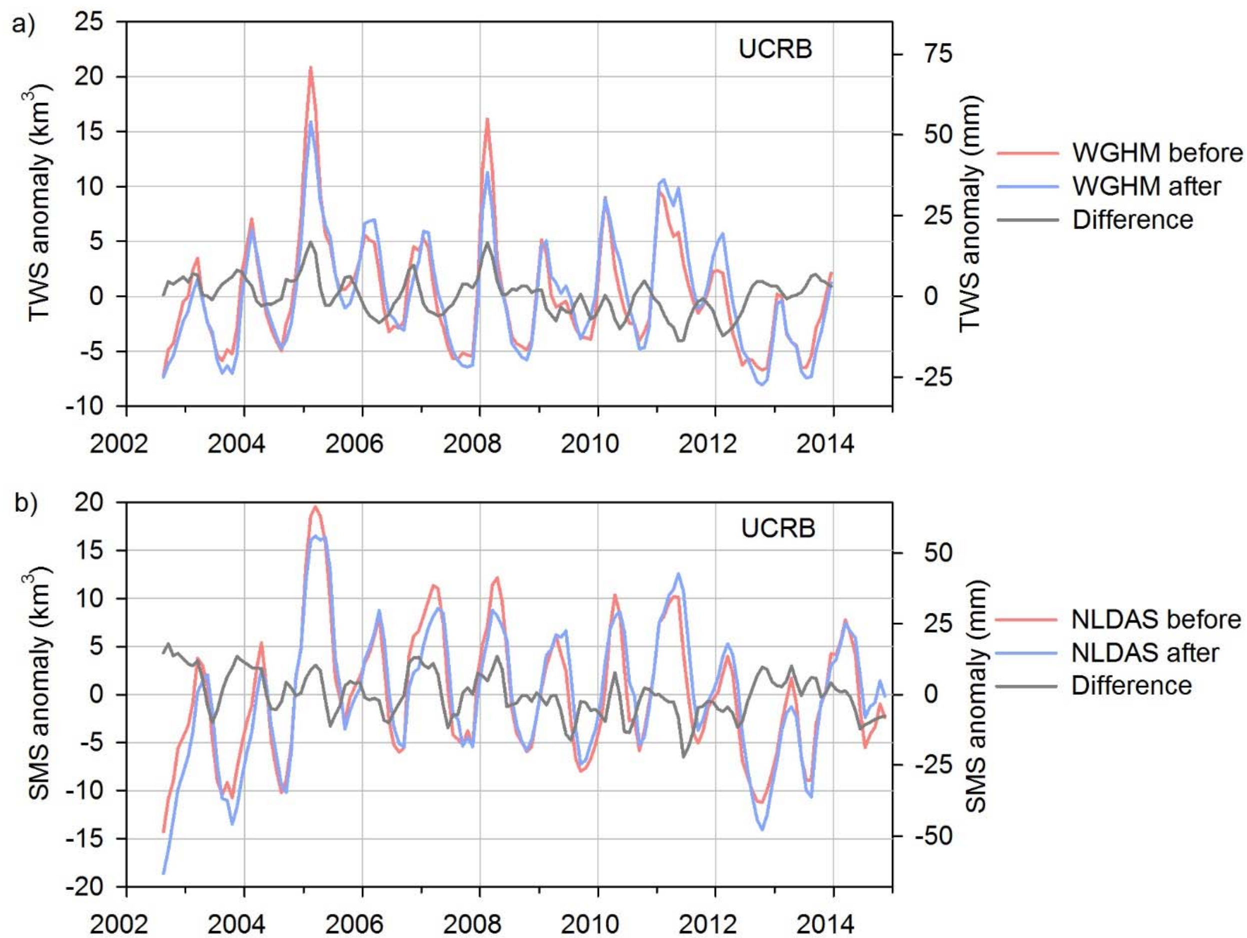

Figure S30. Truncation and filtering applied to (a) WGHM TWS anomalies and (b) NLDAS SMS anomalies in the Upper Colorado River Basin (UCRB) and difference between the unfiltered and filtered output showing effects of truncation and filtering.

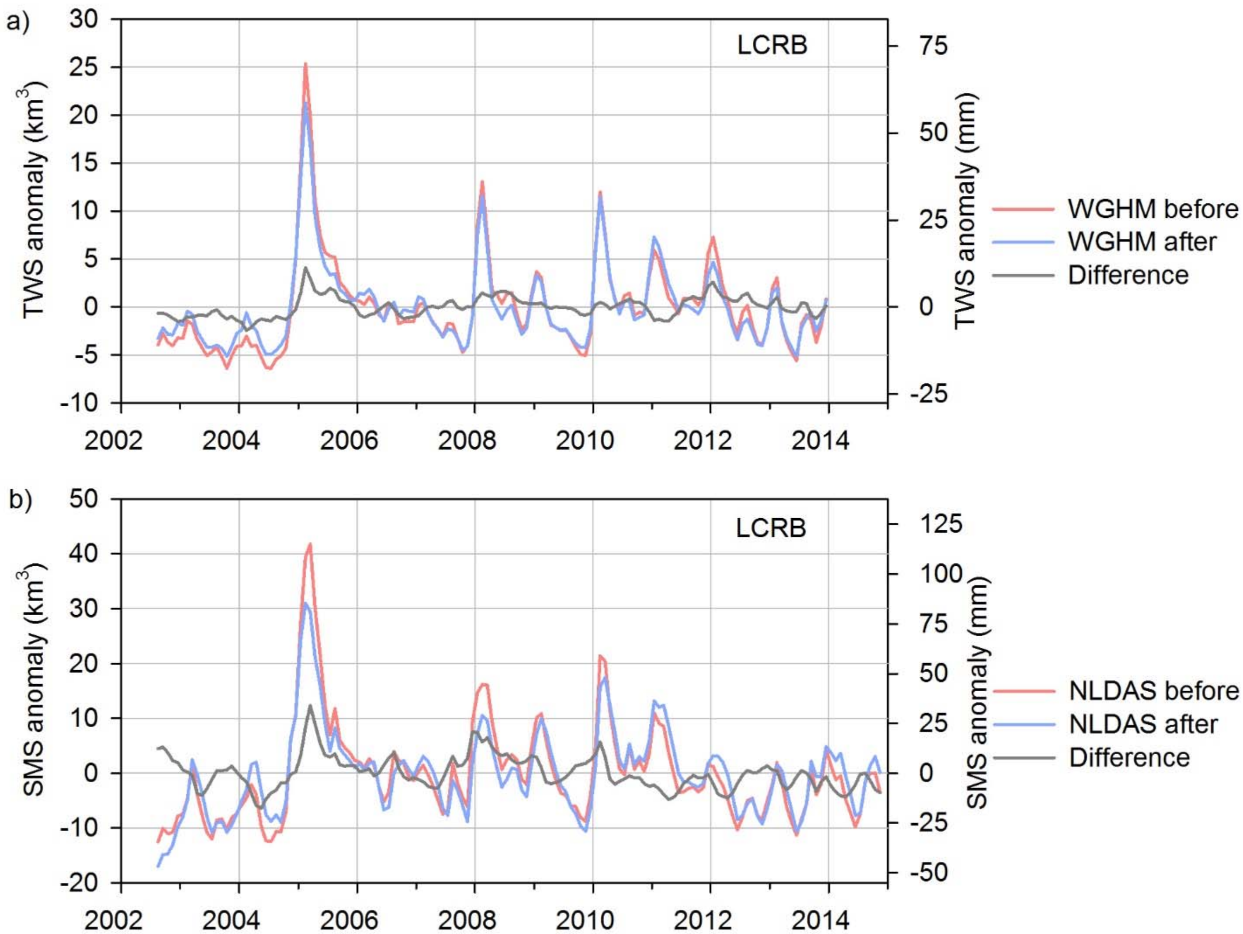

Figure S31. Truncation and filtering applied to (a) WGHM TWS anomalies and (b) NLDAS SMS anomalies in the Lower Colorado River Basin (LCRB) and difference between the unfiltered and filtered output showing effects of truncation and filtering.

Section 5: Ground-based Gravity Surveys

Gravity and land subsidence have been monitored by the Arizona Dept. of Water Resources (ADWR) at networks of stations in the Phoenix and Pinal Active Management Areas (AMAs) beginning in 1999 in the Pinal AMA and 2002 in the Phoenix AMA (Fig. S4). These areas were selected for gravity surveys because of large scale groundwater depletion and conjunctive use of Colorado River water and groundwater, and use of managed aquifer recharge to reverse these trends. Surveys include absolute gravity reference observations by the National Geodetic Survey (NGS) and USGS at one or more stations in each network and relative gravity surveys to calculate absolute-gravity values at each station. The surveys are normally conducted every few years. The networks have sufficient station spatial density to integrate the storage change that has occurred in the network area between any two surveys. The Phoenix AMA includes 90 to 113 stations for each survey covering an area of ~7,100 km^2, including most of the major areas of agriculture and municipal water use. Surveys of the Pinal AMA network included 100 or more stations covering an area of about 2,300 km^2, including all of the major agricultural areas in the AMA. Stations in the Phoenix AMA are primarily located at available monuments at section corners. Many stations in the Pinal AMA network are co-located with wells where depth to water is also measured annually. The dates of the surveys are listed in Table S14, for the periods 2002 – 2009 in the Phoenix AMA and 2000 – 2014 in the Pinal AMA.

Monitoring Ground-based Gravity

Gravity reference observations for each survey were made using falling-mass gravimeters, models FG-5 and A10, manufactured by Micro-g Lacoste Inc. Both meters use laser interferometry to measure the acceleration of a falling reflector in a vacuum. Acceleration is determined by fitting the acceleration parabola equation through time-distance interference fringe pairs. One-thousand or more individual observations of acceleration are averaged to produce the final result. The FG-5 model has a larger vacuum chamber and longer drop length than the field portable A10 model, but requires a stable temperature environment; normally inside a temperature-controlled building. The FG-5 meter is considered to be accurate to ~2 microGal, or equivalent to the gravitational effect of a slab of water that is about 2 inches (50 mm) in thickness. The A10 model reported accuracy is ~ 10 microGal. Intercomparisons of the A10 used in this study with FG5 meters; however, have shown the meter to be equally accurate in a controlled environment (Jiang et al, 2011, Schmerge et al, 2012). Reduced A10 accuracy occurs with field conditions of variable temperature, wind, and local vibrations that compromise observations although care is taken to shield the meter from wind and sun. Records of gravity reference observations include observations made by the NGS using an FG-5 gravimeter through 2007 and observations by the USGS Arizona Water Science Center using an A10 gravimeter beginning in 2009. All reference observations prior to 2014 used the same reference site, Phoenix AA, located in a building on crystalline rock to minimize environmental and hydrologic noise, i.e. the effects of local variations in soil and aquifer storage. Additional reference sites were added to the Pinal AMA network in 2014, including sites that were previously surveyed using relative gravity instruments.

Relative gravity surveys used a factory calibrated CG-3M gravimeter, which is temperature controlled and uses a sensing element based on a fused quartz elastic system. An electrostatic restoring force and a spring are used to balance the gravitational force on the proof mass. Changes in gravity alter the position of the mass. DC voltage is applied to capacitor plates to produce an electrostatic force on the mass, restoring it to a null position. This feedback voltage is a measure of the relative value of gravity among stations in a survey. The surveys used factory calibrations and manufacturer supplied

Earth-tide and weekly calibrated (by ADWR) drift corrections. Several individual surveys that included 2 to 7 stations were completed for each survey of each AMA (http://www.azwater.gov/AzDWR/Hydrology/Geophysics/Reports_Maps.htm, accessed 6/20/2015). All relative surveys were referenced to one or more absolute-gravity observations at reference stations. Repeat measurements at many stations were made by including them in multiple surveys. Many surveys were redone to obtain repeatability of 5 microGal.

Storage change volumes for periods between surveys were developed by interpolating the 1-D storage change across the area of observations for each network. The 1-D storage change was calculated using the Bouguer slab approximation for a layer of water, 41.9 microGal/m. The region between stations was interpolated to create a storage change surface using GIS ordinary Kriging methods and a standard variogram model for all data sets. Interpolation areas were determined by the extent of observations for the data set of smallest extent with buffers around stations of 6 km for Pinal AMA and 8 km for Phoenix AMA (Fig. S4). Regions of non-alluvial surface geology were masked out to omit non-aquifer areas. The storage change surface was gridded to 200 m and the average value for each grid was multiplied by the grid area to produce the total storage change for each interval between surveys. The 2007 survey in the Phoenix AMA was of slightly smaller extent than the other surveys at the easternmost part of the network. Values in the missing extent were assigned average grid values for time periods that included the 2007 survey.

Comparison of Ground-based Gravity Storage Trends with Groundwater-level Records

Ground-based gravity monitors total water storage from the land surface to the Moho, including unsaturated and saturated zones. In contrast, water wells monitor groundwater levels in the aquifer in which the well is screened. The well may be screened in a shallow unconfined aquifer or a deep confined aquifer or the well may be screened across multiple aquifer units. Pool (2008) compared monitored gravity with water-level fluctuations in nearby wells in this region and provided explanations for different correlations between the gravity and water-level data. Because storage changes based on gravity measurements are vertically integrated and wells may only monitor a segment of the system, the two measurements will not necessarily agree. To convert water level changes (ΔWL) in wells to water storage changes (ΔGWS) in an aquifer requires data on the storage coefficient (S):

$$\Delta GWS = S \times \Delta WL$$

Data on GWS from gravity monitoring can be combined with WL changes monitored in wells to estimate storage coefficients (Pool and Eychaner, 1995). Storage coefficients may be up to three orders of magnitude higher in unconfined aquifers than in confined aquifers; therefore, large WL fluctuations in confined aquifers may correspond to small GWS changes.

Good correlation between gravity survey data and WL fluctuations in wells indicate that the wells are screened in the main unconfined aquifer that is responsible for water storage changes and there is little storage change in the unsaturated zone. Poor correlations between the two may reflect large storage changes in the unsaturated zone or in perched aquifers not screened by the wells or wells in confined aquifers. Pool (2008) found one case where water levels were rising in a confined aquifer but gravity was decreasing due to land subsidence. Even where WLs and gravity changes are positively correlated, the magnitude of the storage coefficient can be used to assess the correlation. Storage changes in the unsaturated zone, which is up to 30 -200 m thick in the Phoenix and Pinal AMAs, is common a because of local incidental recharge from agricultural irrigation, artificial recharge facilities, and incidental recharge at canals and ditches, detention basins, dry wells, and turf irrigation.

Application of the two methods allows separation of storage change into two components, the primary aquifer and unsaturated zone, assuming that WL change represents storage change in the primary aquifer. Where storage change occurs locally within only an unconfined aquifer and no storage change occurs in the unsaturated zone, water-level and gravity records indicate storage change in the same subsurface volume, variations in both will correlate, and the ratio of 1D gravity-based storage change to WL change provides an estimate of the storage coefficient or specific yield for unconfined aquifers. Where storage change occurs in only a confined aquifer, gravity variations will be small or unmeasurable and water-level variations may be large, resulting in poor correlation of observations using the two methods. Where significant gravity and water-level variations do not correlate, storage change must also occur in aquifers not screened by the monitoring well or in the unsaturated zone.

The unsaturated zone also includes the shallow few meters that temporarily store infiltrated precipitation and release it through evapotranspiration (ET) to the atmosphere, vegetation, and to deep percolation that eventually recharges the aquifer system. Temporary storage change in this shallow zone can be sufficiently large to be measurable using gravity methods especially following periods of intense precipitation. Gravity values decline as a portion of shallow storage returns to the atmosphere. Any residual deep percolation will continue to result in gravity values that are elevated above the values observed before the period of elevated precipitation. Intense precipitation during winter 2005 may have resulted in elevated storage in the shallow zone that interacts with the atmosphere. Gravity surveys in the Phoenix AMA in March and April 2005 likely captured some of the elevated shallow storage that was later removed through evapotranspiration.

Water-level and gravity correlations are discussed for each period of major gravity-based storage change in the Phoenix and Pinal AMAs. Storage change in the surveyed part of the Phoenix AMA generally increased throughout the monitoring period, 2002 to 2009. However, storage resulting from the spring 2005 survey was anomalously high suggesting an increase in shallow soil storage that was removed from the area through evapotranspiration. Trends in both water-levels and gravity are analyzed for the entire period 2002 to 2014 and for the periods between gravity surveys during spring 2004 to spring 2005 and between the spring 2005 and spring 2007 surveys. Trends in both water-levels and gravity are analyzed for the two major periods of trends in the Pinal AMA, generally increasing storage trends during 1999 to 2008 and a period of storage loss between the 2008 and 2014 surveys.

Phoenix AMA

The results of synoptic gravity surveys are shown in terms of cumulative storage change from the initial survey. Results for the Phoenix AMA show a gradual increase in storage up to May 2004 followed by a rapid increase in May 2005 and a sharp drop in May 2007 and a gradual increase to June 2009. The spike in storage in the spring 2005 survey followed by a rapid decline is attributed to an increase in shallow soil water storage, with most of the water removed by ET. This result is consistent with anomalously high precipitation in winter 2005. Cumulative rates of storage increase are about two times higher in 2005 relative to rates of change between other surveys (Table S14). The overall rate of change is ~0.34 km^3/yr, resulting in 2.4 km^3 increase in storage over the 7 yr period.

Water levels in wells indicated little change in storage before 2005 and an increase in storage after 2005. A large difference in gravity and water-level trends resulted for periods that included the 2005 gravity survey and surveys in 2004 and 2007. Therefore, correlations of gravity and water-level records were analyzed for the periods 2002 – 2004 and 2007 – 2009). Most of the gravity stations in the Phoenix AMA are not co-located with wells, therefore, water levels at wells that were within 4 km of gravity stations were used for comparison with the gravity records.

2002-2004 trends

Gravity-based storage trends indicated slight increases during spring 2002 to spring 2004 of 0.55 km^3 or an average increase of about 0.1 m of water across the survey area. This low amount of change is within the uncertainty of the interpolated change across the network of stations and not significant. Of 78 stations that were surveyed in 2002 and 2004, 45 displayed storage increases, 27 displayed decreases, and change was not detectable, <0.15 m/yr of water storage, at 6 stations. Water levels at wells throughout the AMA also displayed no significant changes in storage. Of 108 water-level records with moderate or better linear correlation trends, r^2>0.4, 55 showed decreasing trends, 46 showed increasing trends, and 7 had no trend (Table S15). Water levels at 44 wells that were within 4 km of the gravity stations included 25 with decreasing trends, 15 increasing, and 4 with no trend (Table S16). Gravity and water-level trends were generally poorly correlated as; only 10 of the gravity/water-level pairs resulted in specific yield values of 0.09 to 0.46. The lack of correlation resulted because 16 sites that indicate a local confined aquifer and 14 sites where significant storage change likely occurs in shallow or perched aquifers. Local confined conditions are indicated at sites with large water-level changes in wells but no detectable gravity change Storage change in shallow aquifers or the unsaturated zone is suggested at sites where significant gravity changes are uncorrelated with y available water-level records.

2007-2009 trends

Gravity-based storage increased slightly during spring 2007 to spring 2009 by 0.82 km^3 or an average increase of about 0.15 m of water across the survey area. This low amount of change is within the uncertainty of the interpolated change across the network of stations and not significant. Of 58 stations that were surveyed in 2007 and 2009, 31 displayed increases, 23 displayed decreases, and 4 had no detectable change in storage. Water levels at wells throughout the AMA generally indicated increasing storage. Of 199 water-level records with moderate or better linear correlation trends during fall 2006 through winter 2010, r^2>0.4, 134 showed increasing trends and 57 showed decreasing trends (Table S15). Of the 199 wells, 51 were within 4 km of 37 gravity stations that had observations in 2007 and 2009 (Table S16). Of these 51 wells, 36 showed rising trends, 10 records showed declining trends, and 5 showed no trends.

Gravity-based storage and water-level trends during 2007-2009 were poorly correlated in general. Only 16 sites with gravity/water-level pairs were well correlated and resulted in specific yield values of 0.02 to 0.43. Gravity change at 1 site was undetectable but water-level changes were large suggesting confined aquifer conditions in the local aquifer system. Another site included undetectable gravity change and no limited water-level change. Gravity and water-level trends displayed opposing trends at 15 sites, specific yield values of >0.50 resulted at 14 sites, and 4 sites had large gravity change and no water-level trend. All three conditions indicate storage change in unmonitored shallow aquifers or unsaturated zone in the local area.

Rising water levels during 2006-2009 suggest that significant recharge occurred as a result of the wet winter of 2005. Gravity records also support an increase in storage at the same time. However, the gravity surveys were completed within weeks of the end of the wet period, ending during February 2005, and likely captured some storage increases in shallow soils that later returned to the atmosphere. As a result, gravity values were temporarily elevated during the 2005 survey causing an anomaly in groundwater storage in comparison with the overall record.

Pinal AMA

Gravity data in the Pinal AMA showed very little change in the first few years followed by a sharp increase during 2002 – 2008 of 1.8 km^3 (mean 0.3 km^3/yr) indicating recovery of aquifer storage (Table S14). A net storage loss of 1.5 km3 (0.26 km3/yr) occurs during 2008 – 2014. Water levels in wells indicated little change in storage before 2008; however, records at only 22 wells restricts the value of the analyses. Storage is likely to have increased during 2010 in response to anomalously high precipitation; however, there is no survey at this time. Water levels during 2008-2014 showed more rise than decline as records at 59 wells showed rises, 38 declines, and no trend at 21 wells. (Table S15). Most of the gravity stations in the Pinal AMA are near wells, therefore, water levels at wells that were within 1 km of gravity stations were used for comparison with the gravity records.

1999-2008 trends

Of 95 gravity stations that were surveyed in 1999 and 2008 and multiple intervening years, 70 displayed increases, 8 displayed decreases, and no detectable change in storage was observed at 17 stations. Conversely, water-levels at wells throughout the AMA generally indicated minimal storage change. Of 43 water-level records with moderate or better linear correlation trends during 1999 through winter 2009, r^2>0.4, 20 showed decreasing trends, 18 showed increasing trends, and 5 showed no trend. Of the 95 wells, 22 were within 1 km of 22 gravity stations that had observations in 1999 and 2008. Of these 22 wells, 7 showed rising trends, 11 records showed declining trends, and 4 had no trends (Table S16).

Gravity-base storage and water-level trends during 1999-2008 were generally poorly correlated. Only 9 of 22 sites with gravity and water-level records resulted in good correlation and specific yield values of 0.04 to 0.18 (Table S16). Insufficient changes in gravity and water-levels occurred at 6 sites. Gravity changes at 2 sites were undetectable; however, but water-level changes were large suggesting confined aquifer conditions in the local aquifer system. Opposing trends in gravity change and water levels were observed at 5 sites, which suggests that storage change has occurred in unmonitored shallow aquifers or unsaturated zone in the local areas.

2008-2014 trends

For the period 2008 to 2014 in the Pinal AMA most gravity records, 44 of 64, are at stations within 1 km of wells that also had water-level records (Table 16). Lack of significant water-level trends at 20 gravity station/well pairs prevented any useful analysis of gravity and water correlations at those sites. Rising water-level trends of 0.2 to 3.5 m/yr occurred at 30 of the wells. Declining water-level trends of 0.03 to 2.0 m/yr occurred at 7 of the wells. Increasing storage rates of 0.06 to 0.38 m/yr of water were observed at 20 of the nearby gravity stations. Storage loss rates of 0.01 to 2.0 m/yr of water were observed at 18 gravity stations. Gravity change was not detected at 6 stations. Most of the sites with increasing storage based on both water level and gravity methods are in the northwest and southeast parts of the gravity station network where storage increases were common during the period of gravity monitoring, 1999-2014.

Positive correlation of gravity-based storage and water-level trends occurred at 23 sites with nearby gravity and groundwater level records resulting in specific yield estimates of 0.06 to 0.45. Storage change in a shallow aquifer and the unsaturated zone likely occurred at 11 data pairs on the basis of opposing water-levels. Gravity trends at 6 sites were greater than can be explained by water-level change in 5 nearby wells. Gravity-based storage change was minimal at 6 stations near wells with water-level records. Water-level trends near these same sites displayed linear trends of 0.3 to 2.5 meters per year suggesting that storage change in the local area at these sites is likely limited to confined aquifers.

Summary of gravity and water-level trend estimates of groundwater storage change

Gravity-based storage and water-level trend based estimates of storage change for the Phoenix and Pinal AMAs display different results. In the Phoenix AMA, fewer gravity/water-level record pairs correlate well and a larger percentage of data pairs suggest substantial storage change occurs in shallow aquifers and the unsaturated zone. Results from both areas suggest that water-levels in wells may not be good indicators of overall groundwater storage change in large parts of the area. Water-level changes in available wells are likely good indicators of storage change in the primary exploited zones of the multiple aquifer systems of the area, but do not monitor storage change in shallow zones that have become active parts of the groundwater flow system. Shallow groundwater flow and storage in the unsaturated zone, perched aquifers, and shallow aquifers that are hydraulically connected to the deep primary aquifer is common in the area because of ephemeral channel infiltration during periods of runoff, incidental recharge of excess irrigation water, incidental recharge at urban turf facilities and detention basins, and artificial recharge of imported surface water and effluent.

About half of the gravity-based storage trends in the Pinal AMA correspond well with water-level trends in nearby wells (Figure S32a). Records for the other half of the gravity/water-level record pairs are not correlated. Poor correlations at some sites are due to a lack of gravity change in areas that may be dominated by storage change in only confined aquifers (Figure S32b). Most of the poor correlation, however, is because of significant gravity changes in shallow or perched aquifers that are not monitored. Water levels at nearby wells are representative of deeper aquifers (Figure S32c, d).

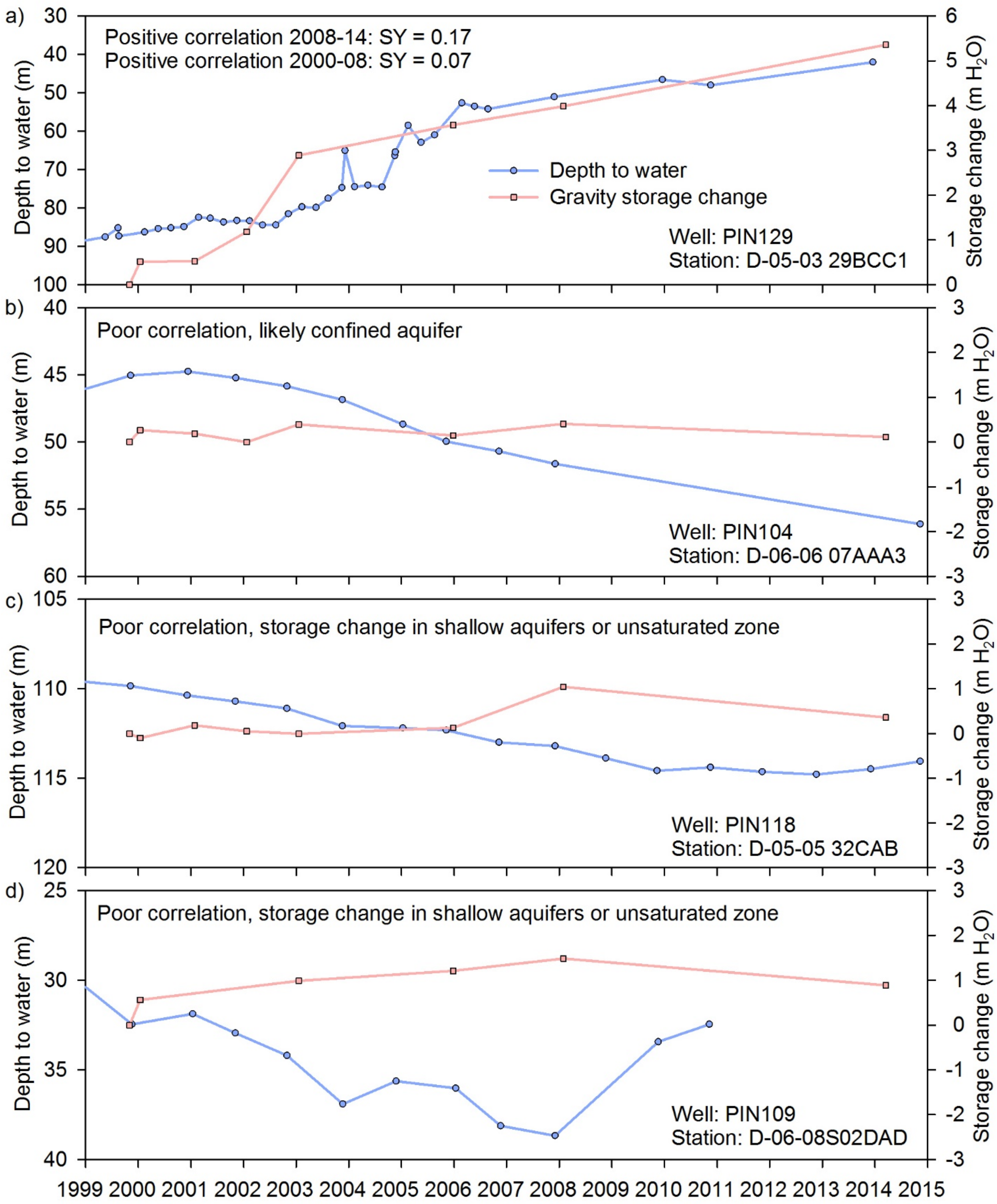

Figure S32. Representative results for different combinations of gravity-survey derived water storage changes compared with nearby water well water-level changes. Blue diamond symbols represent gravity-based water storage changes and red square symbols represent water well depth to water measurements.

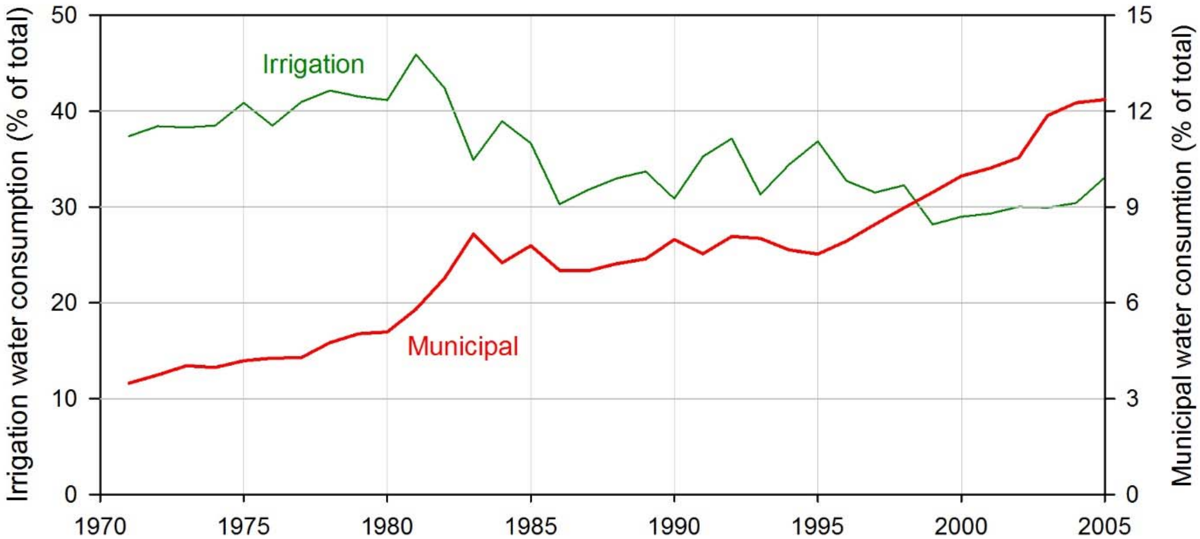

Figure S33. Evolution of water consumption by the irrigation and municipal sectors in the LCRB region, demonstrating that increased municipal water use has been offset primarily by decreased irrigation water use. (http://water.usgs.gov/watuse/)

Table S1. Land use / land cover in the Colorado River Basin (CRB), including the Upper (UCRB) and Lower (LCRB) basin regions based on NLCD (2006). Estimates of total irrigated areas are based on USGS county level water use estimates (USGS Circular 1344, http://water.usgs.gov/watuse/data/2005/) and on Modis satellite imagery 2007 (http://earlywarning.usgs.gov/USirrigation).

Category	*Area (km^2)*			*% of Total Area*		
	CRB	*UCRB*	*LCRB*	*CRB*	*UCRB*	*LCRB*
Shrubland	409,888	153,371	256,516	62.4	52.2	70.7
Forest	146,343	83,459	62,884	22.3	28.4	17.3
Grassland	47,046	26,653	20,394	7.2	9.1	5.6
Barren	21,836	15,363	6,473	3.3	5.2	1.8
Developed	10,584	2,562	8,023	1.6	0.9	2.2
Pasture/Hay	7,556	6,183	1,373	1.2	2.1	0.4
Crops	6,022	1,436	4,586	0.9	0.5	1.3
Open Water/Wetlands	7,379	4,884	2,495	1.1	1.7	0.7
Total	656,655	293,911	362,744	100.0	100.0	100.0
Irrigated (USGS 2005)	9,445	5,051	4,394	1.4	1.7	1.2
Irrigated (Modis 2007)	9,125	5,025	4,100	1.4	1.7	1.1

Table S2. Water withdrawals in the Upper and Lower Colorado River basins based on USGS county level water use reports (http://water.usgs.gov/watuse/data/). Populations are in millions. Values are in km^3. Values were estimated in part based on county area land use percentages within each basin.

Region	*Category*	*1985*	*1990*	*1995*	*2000*	*2005*	*2010*
Upper Colorado River Basin	Population	0.66	0.65	0.74	0.82	0.89	0.97
	Total withdrawal	10.33	9.76	9.82	9.42	9.84	9.03
	Total groundwater	0.25	0.26	0.20	0.41	0.38	0.38
	Total surface water	10.08	9.49	9.61	9.01	9.45	8.65
	Irrigation	9.82	9.10	9.29	8.72	9.10	8.33
	Municipal	0.18	0.17	0.20	0.24	0.23	0.23
	Mining	0.08	0.08	0.03	0.08	0.09	0.09
	Steam electric	0.15	0.23	0.18	0.25	0.25	0.19
	Domestic	0.01	0.01	0.02	0.03	0.02	0.03
	Industrial	0.02	0.02	0.02	0.01	0.02	0.01
	Livestock	0.05	0.15	0.08	0.00	0.01	0.01
	Aquaculture	0.00	0.00	0.00	0.09	0.11	0.13
Lower Colorado River Basin	Population	4.13	4.79	5.67	6.67	7.85	8.56
	Total withdrawal	10.29	10.52	10.60	8.99	8.46	8.14
	Total groundwater	4.77	4.56	4.46	4.18	3.89	3.40
	Total surface water	5.51	5.97	6.55	4.71	4.57	4.74
	Irrigation	8.55	8.13	8.67	6.78	5.95	5.59
	Municipal	1.24	1.49	1.75	1.89	2.09	2.04
	Mining	0.15	0.27	0.25	0.10	0.15	0.19
	Steam electric	0.09	0.16	0.18	0.13	0.12	0.11
	Domestic	0.05	0.06	0.06	0.05	0.07	0.05
	Industrial	0.10	0.28	0.10	0.03	0.03	0.02
	Livestock	0.10	0.06	0.06	0.01	0.02	0.03
	Aquaculture	0.00	0.00	0.00	0.00	0.04	0.09

Table S3a. Reservoirs in the Upper Colorado River Basin. Total listed reservoir capacity is 42.62 km^3. Percent of total represents percentage of total reservoir storage capacity in the UCRB. Entries in **bold** represent reservoirs with storage volume monitoring used in this analysis.

*Owner/ Agency**	*Dam Name*	*Reservoir Name*	*State*	*Capacity (km^3)*	*% of Total*	*Elevation (m)*	*Year Impounded*
Colorado River main stem and upper tributaries – 31.50 km^3							
USBR	**Glen Canyon**	**Powell**	**AZ**	**29.99**	**70.4**	**1,128**	**1966**
USBR	**Granby**	**Granby**	**CO**	**0.67**	**1.6**	**2,524**	**1950**
DW	Dillon	Dillon	CO	0.31	0.7	2,748	1963
USBR	Green Mountain	Green Mountain	CO	0.19	0.4	2,423	1942
USBR	Ruedi	Ruedi	CO	0.13	0.3	2,365	1968
DW	Williams Fork	Williams Fork	CO	0.12	0.3	2,381	1959
CRWCD	Wolford Mountain	Wolford Mountain	CO	0.08	0.2	2,257	1996
USBR	Shadow Mountain	Shadow Mountain	CO	0.02	0.1	2,550	1946
Green River and tributaries – 7.04 km^3							
USBR	**Flaming Gorge**	**Flaming Gorge**	**CO**	**4.67**	**11.0**	**1,841**	**1964**
USBR	**Soldier Creek**	**Strawberry**	**UT**	**1.36**	**3.2**	**2,317**	**1974**
USBR	**Fontenelle**	**Fontenelle**	**WY**	**0.43**	**1.0**	**1,983**	**1964**
USBR	Starvation	Starvation	UT	0.21	0.5	1,741	1970
USBR	Scofield	Scofield	UT	0.09	0.2	2,322	1946
USBR	Joes Valley	Joes Valley	UT	0.08	0.2	2,131	1966
USBR	Moon Lake	Moon Lake	UT	0.06	0.1	2,480	1938
USBR	Big Sandy	Big Sandy	WY	0.05	0.1	2,060	1952
USBR	Upper Stillwater	Upper Stillwater	UT	0.04	0.1	2,521	1987
USBR	Meeks Cabin	Meeks Cabin	UT	0.04	0.1	2,647	1971
USBR	Stateline	Stateline	UT	0.01	0.03	2,793	1979
Gunnison River and tributaries – 1.43 km^3							
USBR	**Blue Mesa**	**Blue Mesa**	**CO**	**1.02**	**2.4**	**2,292**	**1965**
USBR	Morrow Point	Morrow Point	CO	0.14	0.3	2,182	1968
USBR	Taylor Park	Taylor Park	CO	0.13	0.3	2,844	1937
USBR	Ridgway	Ridgway	CO	0.10	0.2	2,085	1987
USBR	Crystal	Crystal	CO	0.03	0.1	2,059	1977
Dolores River – 0.34 km^3							
USBR	**McPhee**	**McPhee**	**CO**	**0.34**	**0.8**	**2,110**	**1984**
San Juan River and tributaries – 2.30 km^3							
USBR	**Navajo**	**Navajo**	**NM**	**2.09**	**4.9**	**1,855**	**1962**
USBR	Vallecito	Vallecito	CO	0.16	0.4	2,336	1941
USBR	Lemon	Lemon	CO	0.05	0.1	2,482	1963

* *CRWCD*: Colorado River Water Conservation District, *DW*: Denver Water, *USBR*: US Bureau of Reclamation

Table S3b. Reservoirs in the Lower Colorado River Basin. Total listed reservoir capacity is 44.83 km^3. Percent of total represents percentage of total reservoir storage capacity in the LCRB. Entries in **bold** represent reservoirs with storage volume monitoring used in this analysis.

*Owner/ Agency**	*Dam Name*	*Lake / Reservoir Name*	*State*	*Capacity (km^3)*	*% of Total*	*Elevation (m)*	*Year Impounded*
Colorado River main stem – 35.10 km^3							
USBR	**Hoover**	**Mead**	**AZ/NV**	**31.91**	**71.1**	**372**	**1936**
USBR	**Davis**	**Mohave**	**AZ/NV**	**2.23**	**5.0**	**197**	**1951**
USBR	**Parker**	**Havasu**	**AZ/CA**	**0.76**	**1.7**	**137**	**1938**
USBR	Imperial	Imperial	AZ/CA	0.20	0.4	56	1938
Bill Williams River – 1.29 km^3							
USACE	**Alamo**	**Alamo**	**AZ**	**1.29**	**2.9**	**336**	**1968**
Gila River and Agua Fria River – 5.56 km3							
USACE	**Painted Rock**	**Painted Rock**	**AZ**	**3.07**	**6.9**	**201**	**1960**
USBR/CAP	**New Waddell**	**Pleasant**	**AZ**	**1.37**	**3.0**	**526**	**1994**
BIA	**Coolidge**	**San Carlos**	**AZ**	**1.12**	**2.5**	**773**	**1930**
Salt River and Verde River – 2.88 km^3							
USBR	**Theodore Roosevelt**	**Theodore Roosevelt**	**AZ**	**2.04**	**4.5**	**656**	**1911**
USBR	Horse Mesa	Apache	AZ	0.30	0.7	576	1927
USBR	Bartlett	Bartlett	AZ	0.22	0.5	548	1939
USBR	Horseshoe	Horseshoe	AZ	0.16	0.4	618	1946
USBR	Stewart Mountain	Saguaro	AZ	0.09	0.2	466	1930
USBR	Mormon Flat	Canyon	AZ	0.07	0.2	491	1926

* *BIA*: Bureau of Indian Affairs, *USACE*: US Army Corps of Engineers, *USBR*: US Bureau of Reclamation, *CAP*: Central Arizona Project

Table S4. Wettest and driest water years in the UCRB and LCRB for the 115 year period 1900 – 2014. Values shown represent wettest/driest rank, year of occurrence, and total annual precipitation depth. (http://www.prism.oregonstate.edu/)

Wettest Rank	*UCRB*		*LCRB*			*Driest Rank*	*UCRB*		*LCRB*	
	Year	*mm*	*Year*	*mm*			*Year*	*mm*	*Year*	*mm*
1	1997	546	1941	531		1	1977	254	1956	162
2	1995	523	1905	484		2	2002	261	2002	164
3	1941	504	1983	484		3	1902	261	2000	183
4	1986	501	2005	462		4	1934	264	1902	196
5	1909	500	1993	462		5	1931	282	1900	205
6	1984	500	1979	459		6	1924	291	1904	208
7	1973	490	1992	459		7	2012	295	1974	213
8	1927	489	1973	440		8	1956	296	1996	214
9	1965	487	1915	429		9	1974	298	1989	217
10	1957	486	1907	413		10	1953	306	1950	227
11	1982	483	1958	406		11	2000	311	2009	227
12	2005	480	1906	405		12	1960	312	1959	232
13	1983	479	1919	400		13	1989	313	1928	233
14	1906	476	1916	400		14	1966	316	1953	236
15	1999	475	1927	399		15	1900	320	1910	236
16	1929	475	1998	395		16	1910	320	1971	237
17	1952	470	1988	395		17	1928	324	1947	241
18	2011	466	1995	389		18	1951	324	1934	245
19	1914	462	1985	388		19	1955	325	1948	246
20	1993	462	1978	384		20	1933	326	2006	249

Table S5. Time periods of warm and cool phases of the Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO).

Event	*Period*	*Character*
AMO	1900 – 1925	Cool
	1925 – 1965	Warm
	1965 – 1994	Cool
	1994 – 2015	Warm
PDO	1890 – 1924	Cool
	1925 – 1946	Warm
	1947 – 1976	Cool
	1977 – 1997	Warm
	1998 – 2015	Cool

Table S6. Time periods of different intensities of El Niño Southern Oscillation (ENSO) events (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

El Niño				*La Niña*		
Weak	*Mod*	*Strong*	*Very Strong*	*Weak*	*Mod*	*Strong*
1951-52	1963-64	1957-58	1982-83	1950-51	1955-56	1973-74
1952-53	1986-87	1965-66	1997-98	1954-55	1970-71	1975-76
1953-54	1987-88	1972-73		1964-65	1998-99	1988-89
1958-59	1991-92			1967-68	1999-00	2010-11
1968-69	2002-03			1971-72	2007-08	
1969-70	2009-10			1974-75		
1976-77				1983-84		
1977-78				1984-85		
1979-80				1995-96		
1994-95				2000-01		
2004-05				2011-12		
2006-07						

Table S7. Historical values and characterizations of the El Niño Southern Oscillation (ENSO) for the 1950-51 through 1981-82 seasons. ENSO Seasons begin in July and end the following June. Values represent 3-month moving averages. Values in **red** represent El Niño periods and values in **blue** represent La Niña periods. Types include weak (W), moderate (M), strong (S), and very strong (VS) (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml)

Type	*Season*	*JJA*	*JAS*	*ASO*	*SON*	*OND*	*NDJ*	*DJF*	*JFM*	*FMA*	*MAM*	*AMJ*	*MJJ*
W	1950-51	**-0.6**	**-0.6**	**-0.5**	**-0.6**	**-0.7**	**-0.8**	**-0.8**	**-0.6**	-0.2	0.2	0.2	0.4
W	1951-52	**0.5**	**0.7**	**0.8**	**0.9**	**0.7**	**0.6**	**0.5**	0.4	0.4	0.4	0.4	0.2
W	1952-53	0.0	0.1	0.2	0.2	0.2	0.3	**0.5**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**
W	1953-54	**0.7**	**0.7**	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	0.4	0.0	-0.4	**-0.5**	**-0.5**
W	1954-55	**-0.5**	**-0.7**	**-0.7**	**-0.6**	**-0.5**	**-0.5**	**-0.6**	**-0.6**	**-0.7**	**-0.7**	**-0.7**	**-0.6**
M	1955-56	**-0.6**	**-0.6**	**-1.0**	**-1.4**	**-1.6**	**-1.4**	**-0.9**	**-0.6**	**-0.6**	**-0.5**	**-0.5**	-0.4
	1956-57	-0.5	-0.5	-0.4	-0.4	-0.5	-0.4	-0.3	0.0	0.3	**0.6**	**0.7**	**0.9**
S	1957-58	**1.0**	**1.2**	**1.1**	**1.2**	**1.3**	**1.6**	**1.7**	**1.5**	**1.2**	**0.8**	**0.7**	**0.6**
W	1958-59	**0.5**	0.4	0.4	**0.5**	**0.6**	**0.6**	**0.6**	**0.5**	0.4	0.2	0.1	-0.2
	1959-60	-0.3	-0.3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.1	0.0	-0.1	-0.2
	1960-61	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	-0.1	0.0	0.1	0.2
	1961-62	0.1	-0.1	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.2
	1962-63	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.2	0.1	0.2	0.2	0.4
M	1963-64	**0.7**	**1.0**	**1.1**	**1.2**	**1.2**	**1.1**	**1.0**	**0.6**	0.1	-0.3	**-0.6**	**-0.6**
W	1964-65	**-0.7**	**-0.7**	**-0.8**	**-0.8**	**-0.8**	**-0.8**	**-0.5**	-0.3	-0.1	0.1	0.4	**0.7**
S	1965-66	**1.0**	**1.3**	**1.6**	**1.7**	**1.8**	**1.5**	**1.3**	**1.0**	**0.9**	**0.6**	0.3	0.2
	1966-67	0.2	0.1	0.0	-0.1	-0.1	-0.3	-0.4	-0.5	-0.5	-0.5	-0.2	0.0
W	1967-68	0.0	-0.2	-0.3	-0.4	-0.4	**-0.5**	**-0.7**	**-0.8**	**-0.7**	**-0.5**	-0.1	0.2
W	1968-69	0.5	0.4	0.3	0.4	**0.6**	**0.8**	**0.9**	**1.0**	**0.9**	**0.7**	**0.6**	**0.5**
W	1969-70	0.4	**0.5**	**0.8**	**0.8**	**0.8**	**0.7**	**0.6**	0.4	0.4	0.3	0.1	-0.3
M	1970-71	**-0.6**	**-0.8**	**-0.8**	**-0.8**	**-0.9**	**-1.2**	**-1.3**	**-1.3**	**-1.1**	**-0.9**	**-0.8**	**-0.7**
W	1971-72	**-0.8**	**-0.7**	**-0.8**	**-0.8**	**-0.9**	**-0.8**	**-0.7**	-0.4	0.0	0.3	**0.6**	**0.8**
S	1972-73	**1.1**	**1.3**	**1.5**	**1.8**	**2.0**	**1.9**	**1.7**	**1.2**	**0.6**	0.0	-0.4	**-0.8**
S	1973-74	**-1.0**	**-1.2**	**-1.4**	**-1.7**	**-1.9**	**-1.9**	**-1.7**	**-1.5**	**-1.2**	**-1.0**	**-0.9**	**-0.8**
W	1974-75	**-0.6**	-0.4	-0.4	**-0.6**	**-0.7**	**-0.6**	**-0.5**	**-0.5**	**-0.6**	**-0.6**	**-0.7**	**-0.8**
S	1975-76	**-1.0**	**-1.1**	**-1.3**	**-1.4**	**-1.5**	**-1.6**	**-1.5**	**-1.1**	**-0.7**	-0.4	-0.3	-0.1
W	1976-77	0.1	0.3	**0.5**	**0.7**	**0.8**	**0.8**	**0.7**	**0.6**	0.4	0.3	0.3	0.4
W	1977-78	0.4	0.4	**0.5**	**0.6**	**0.8**	**0.8**	**0.7**	0.4	0.1	-0.2	-0.3	-0.3
	1978-79	-0.4	-0.4	-0.4	-0.3	-0.1	0.0	0.0	0.1	0.2	0.3	0.3	0.1
W	1979-80	0.1	0.2	0.3	**0.5**	**0.5**	**0.6**	**0.6**	**0.5**	0.3	0.4	0.5	0.5
	1980-81	0.3	0.2	0.0	0.1	0.1	0.0	-0.2	-0.4	-0.4	-0.3	-0.2	-0.3
	1981-82	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.0	0.1	0.2	**0.5**	**0.6**	**0.7**

Table S7 (cont). Historical values and characterizations of the El Niño Southern Oscillation (ENSO) for the 1982-83 through 2014-15 seasons. ENSO Seasons begin in July and end the following June. Values represent 3-month moving averages. Values in **red** represent El Niño periods and values in **blue** represent La Niña periods. Types include weak (W), moderate (M), strong (S), and very strong (VS) (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

Type	*Season*	*JJA*	*JAS*	*ASO*	*SON*	*OND*	*NDJ*	*DJF*	*JFM*	*FMA*	*MAM*	*AMJ*	*MJJ*
VS	1982-83	**0.8**	**1.0**	**1.5**	**1.9**	**2.1**	**2.1**	**2.1**	**1.8**	**1.5**	**1.2**	**1.0**	**0.7**
W	1983-84	0.3	0.0	-0.3	-0.6	-0.8	-0.8	-0.5	-0.3	-0.3	-0.4	-0.4	-0.4
W	1984-85	-0.3	-0.2	-0.3	**-0.6**	**-0.9**	**-1.1**	**-0.9**	**-0.7**	**-0.7**	**-0.7**	**-0.7**	**-0.6**
	1985-86	-0.4	-0.4	-0.4	-0.3	-0.2	-0.3	-0.4	-0.4	-0.3	-0.2	-0.1	0.0
M	1986-87	0.2	0.4	**0.7**	**0.9**	**1.0**	**1.1**	**1.1**	**1.2**	**1.1**	**1.0**	**0.9**	**1.1**
M	1987-88	**1.4**	**1.6**	**1.6**	**1.4**	**1.2**	**1.1**	**0.8**	**0.5**	0.1	-0.3	**-0.8**	**-1.2**
S	1988-89	**-1.2**	**-1.1**	**-1.2**	**-1.4**	**-1.7**	**-1.8**	**-1.6**	**-1.4**	**-1.1**	**-0.9**	**-0.6**	-0.4
	1989-90	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	0.1	0.2	0.2	0.2	0.2	0.3
	1990-91	0.3	0.3	0.4	0.3	0.4	0.4	0.4	0.3	0.2	0.2	0.4	**0.6**
M	1991-92	**0.7**	**0.7**	**0.7**	**0.8**	**1.2**	**1.4**	**1.6**	**1.5**	**1.4**	**1.2**	**1.0**	**0.8**
	1992-93	**0.5**	0.2	0.0	-0.1	-0.1	0.0	0.2	0.3	0.5	0.7	0.8	0.6
	1993-94	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.3	0.4	0.4
W	1994-95	0.4	0.4	0.4	**0.6**	**0.9**	**1.0**	**0.9**	**0.7**	**0.5**	0.3	0.2	0.0
W	1995-96	-0.2	**-0.5**	**-0.7**	**-0.9**	**-1.0**	**-0.9**	**-0.9**	**-0.7**	**-0.6**	-0.4	-0.2	-0.2
	1996-97	-0.2	-0.3	-0.3	-0.4	-0.4	-0.5	-0.5	-0.4	-0.2	0.1	**0.6**	**1.0**
VS	1997-98	**1.4**	**1.7**	**2.0**	**2.2**	**2.3**	**2.3**	**2.1**	**1.8**	**1.4**	**1.0**	**0.5**	-0.1
M	1998-99	**-0.7**	**-1.0**	**-1.2**	**-1.2**	**-1.3**	**-1.4**	**-1.4**	**-1.2**	**-1.0**	**-0.9**	**-0.9**	**-1.0**
M	1999-00	**-1.0**	**-1.0**	**-1.1**	**-1.2**	**-1.4**	**-1.6**	**-1.6**	**-1.4**	**-1.1**	**-0.9**	**-0.7**	**-0.7**
W	2000-01	**-0.6**	**-0.5**	**-0.6**	**-0.7**	**-0.8**	**-0.8**	**-0.7**	**-0.6**	**-0.5**	-0.3	-0.2	-0.1
	2001-02	0.0	-0.1	-0.1	-0.2	-0.3	-0.3	-0.2	-0.1	0.1	0.2	0.4	**0.7**
M	2002-03	**0.8**	**0.9**	**1.0**	**1.2**	**1.3**	**1.1**	**0.9**	**0.6**	0.4	0.0	-0.2	-0.1
	2003-04	0.1	0.2	0.3	0.4	0.4	0.4	0.3	0.2	0.1	0.1	0.2	0.3
W	2004-05	**0.5**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.6**	**0.6**	**0.5**	**0.5**	0.4	0.2
	2005-06	0.1	0.0	0.0	-0.1	-0.4	-0.7	-0.7	-0.6	-0.4	-0.2	0.0	0.1
W	2006-07	0.2	0.3	**0.5**	**0.8**	**0.9**	**1.0**	**0.7**	0.3	0.0	-0.1	-0.2	-0.2
M	2007-08	-0.3	**-0.6**	**-0.8**	**-1.1**	**-1.2**	**-1.3**	**-1.4**	**-1.3**	**-1.1**	**-0.9**	**-0.7**	**-0.5**
	2008-09	-0.3	-0.2	-0.2	-0.3	-0.5	-0.7	-0.8	-0.7	-0.4	-0.1	0.2	0.4
M	2009-10	**0.5**	**0.6**	**0.7**	**1.0**	**1.2**	**1.3**	**1.3**	**1.1**	**0.8**	**0.5**	0.0	-0.4
M	2010-11	**-0.8**	**-1.1**	**-1.3**	**-1.4**	**-1.3**	**-1.4**	**-1.3**	**-1.1**	**-0.8**	**-0.6**	-0.3	-0.2
W	2011-12	-0.3	**-0.5**	**-0.7**	**-0.9**	**-0.9**	**-0.8**	**-0.7**	**-0.6**	**-0.5**	-0.4	-0.3	-0.1
	2012-13	0.1	0.3	0.4	0.4	0.2	-0.2	-0.4	-0.5	-0.3	-0.2	-0.2	-0.2
	2013-14	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.5	-0.6	-0.4	-0.2	0.0	0.0
	2014-15	0.0	0.0	0.2	0.4	0.6	0.6	0.5	0.4	0.5	0.7	0.9	1.0

Table S8a. Consumptive uses and losses summary for the Upper Colorado River Basin based on US Bureau of Reclamation reports. Values are in km^3. Evaporation represent total estimated reservoir evaporation, Stock represents direct stock use and evaporation from stock ponds, SE represent thermoelectric generation cooling losses, Municipal represents municipal, rural domestic, and industrial consumption. (http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html)

Year	*Total*	*Evaporation*	*Exports*	*Irrigation*	*Stock*	*Mining*	*SE*	*Municipal*
1971	4.19	0.71	0.72	2.58	0.05	0.05	0.04	0.04
1972	4.30	0.74	0.82	2.55	0.05	0.05	0.04	0.04
1973	4.18	0.77	0.90	2.32	0.04	0.05	0.04	0.05
1974	4.68	0.90	0.84	2.73	0.05	0.06	0.06	0.05
1975	4.41	0.89	1.01	2.30	0.04	0.06	0.07	0.05
1976	4.36	0.94	0.86	2.35	0.03	0.06	0.09	0.04
1977	3.75	0.88	0.77	1.84	0.03	0.06	0.12	0.04
1978	4.73	0.86	1.05	2.57	0.03	0.06	0.11	0.04
1979	4.84	0.93	0.99	2.66	0.03	0.06	0.12	0.04
1980	4.80	1.06	0.80	2.65	0.03	0.06	0.14	0.04
1981	4.92	0.95	0.86	2.81	0.05	0.06	0.14	0.06
1982	4.94	0.88	1.01	2.75	0.05	0.05	0.15	0.06
1983	4.83	1.02	0.71	2.81	0.05	0.04	0.14	0.06
1984	4.82	1.09	0.72	2.72	0.05	0.03	0.15	0.06
1985	5.12	1.06	0.83	2.93	0.04	0.03	0.16	0.07
1986	5.02	1.05	0.86	2.81	0.04	0.03	0.16	0.08
1987	5.21	1.14	0.70	3.04	0.04	0.03	0.18	0.08
1988	5.73	1.12	0.90	3.36	0.04	0.03	0.19	0.08
1989	5.79	1.07	0.97	3.40	0.05	0.03	0.20	0.08
1990	5.39	0.94	0.87	3.25	0.04	0.03	0.19	0.08
1991	5.36	0.84	0.94	3.25	0.04	0.03	0.18	0.08
1992	5.57	0.87	0.93	3.43	0.04	0.03	0.19	0.08
1993	5.28	0.93	1.07	2.93	0.04	0.02	0.20	0.08
1994	5.97	1.00	0.94	3.67	0.05	0.02	0.21	0.08
1995	4.92	1.01	0.80	2.76	0.05	0.02	0.19	0.09
1996	5.56	1.11	0.85	3.26	0.04	0.02	0.20	0.09
1997	5.29	1.12	1.00	2.82	0.04	0.01	0.20	0.09
1998	5.43	1.16	0.79	3.12	0.04	0.01	0.21	0.10
1999	5.21	1.16	0.82	2.87	0.04	0.01	0.21	0.10
2000	5.69	1.11	0.97	3.26	0.04	0.01	0.20	0.10
2001	5.96	1.05	1.13	3.42	0.04	0.01	0.21	0.10
2002	5.29	0.90	0.82	3.20	0.04	0.01	0.21	0.10
2003	5.20	0.80	0.89	3.14	0.04	0.01	0.20	0.11
2004	4.82	0.71	0.90	2.84	0.04	0.01	0.21	0.11
2005	4.98	0.77	0.98	2.86	0.04	0.01	0.21	0.11
2006	5.28	0.85	1.07	2.99	0.04	0.01	0.21	0.11
2007	5.61	0.86	0.95	3.44	0.04	0.01	0.20	0.10
2008	5.74	0.90	1.18	3.30	0.04	0.01	0.20	0.10
2009	5.65	0.96	0.97	3.36	0.04	0.01	0.20	0.10
2010	5.46	0.94	0.86	3.30	0.04	0.01	0.20	0.11
2011	5.38	0.99	1.04	2.99	0.04	0.01	0.20	0.11
2012	5.72	0.93	0.94	3.50	0.04	0.01	0.19	0.11
2013	4.94	0.79	0.83	2.96	0.04	0.01	0.20	0.11
Average	5.12	0.95	0.90	2.96	0.04	0.03	0.17	0.08
Min	3.75	0.71	0.70	1.84	0.03	0.01	0.04	0.04
Max	5.97	1.16	1.18	3.67	0.05	0.06	0.21	0.11

Table S8b. Consumptive uses and losses summary for the Lower Colorado River Basin Main Stem based on US Bureau of Reclamation reports. Values are in km^3. Evaporation represent total estimated reservoir evaporation, SE represent thermoelectric generation cooling losses, Municipal represents municipal, rural domestic, industrial, livestock, and mining consumption. Data are not publically available after 2005. (http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html)

Year	*Total**	*Evaporation*	*Exports*	*Irrigation*	*SE*	*Municipal*	*Mexico*
1971	8.03	1.36	5.71	0.88	0.01	0.08	1.92
1972	8.26	1.34	5.94	0.84	0.01	0.12	1.97
1973	7.87	1.37	5.65	0.71	0.01	0.13	1.97
1974	8.55	1.43	6.13	0.83	0.02	0.14	2.12
1975	7.90	1.43	5.50	0.82	0.02	0.13	2.04
1976	7.68	1.49	5.35	0.70	0.02	0.13	2.16
1977	7.62	1.45	5.39	0.63	0.02	0.13	2.26
1978	7.39	1.26	5.11	0.87	0.01	0.14	2.15
1979	7.24	1.30	5.07	0.71	0.01	0.15	3.41
1980	7.39	1.41	5.19	0.61	0.02	0.17	7.57
1981	7.91	1.24	5.25	1.21	0.02	0.19	4.93
1982	7.13	1.21	4.73	0.97	0.02	0.19	2.24
1983	6.40	1.36	4.44	0.39	0.02	0.19	12.06
1984	7.44	1.23	5.29	0.70	0.02	0.20	20.95
1985	7.53	1.32	5.35	0.63	0.01	0.22	16.52
1986	7.83	1.35	5.46	0.77	0.02	0.24	13.47
1987	8.41	1.27	5.83	1.03	0.02	0.26	5.85
1988	8.87	1.14	6.14	1.27	0.02	0.29	3.03
1989	9.42	1.22	6.57	1.27	0.02	0.34	2.13
1990	9.58	1.29	6.68	1.22	0.02	0.37	2.07
1991	8.69	1.36	6.07	0.99	0.02	0.25	2.05
1992	8.17	0.98	5.76	1.17	0.02	0.25	2.07
1993	8.99	1.46	6.56	0.66	0.02	0.29	6.48
1994	9.39	1.38	6.67	1.01	0.02	0.32	2.03
1995	9.08	1.30	6.38	1.07	0.02	0.31	2.27
1996	10.22	1.67	7.29	0.88	0.02	0.36	1.99
1997	10.29	1.59	7.58	0.75	0.02	0.35	3.66
1998	9.69	1.29	7.08	0.95	0.02	0.35	5.96
1999	10.13	1.80	7.43	0.48	0.02	0.41	3.67
2000	10.22	1.77	7.38	0.59	0.02	0.45	2.64
2001	10.37	1.53	7.63	0.75	0.02	0.44	2.22
2002	10.68	1.41	7.77	1.03	0.02	0.46	2.15
2003	9.29	1.32	6.96	0.59	0.01	0.41	2.07
2004	9.12	1.26	6.81	0.65	0.02	0.39	2.09
2005	8.75	0.92	6.53	0.88	0.02	0.40	2.13
2006	-	-	-	-	-	-	2.03
2007	-	-	-	-	-	-	2.01
2008	-	-	-	-	-	-	2.10
2009	-	-	-	-	-	-	2.07
2010	-	-	-	-	-	-	2.21
2011	-	-	-	-	-	-	2.11
2013	-	-	-	-	-	-	2.12
Mean	8.62	1.36	6.13	0.84	0.02	0.26	3.93
Min	6.40	0.92	4.44	0.39	0.01	0.08	1.92
Max	10.68	1.80	7.77	1.27	0.02	0.46	20.95

*Does not include discharge to Mexico.

Table S8c. Consumptive uses and losses summary for the Lower Colorado River Basin (including Main Stem in Table S8b) based on US Bureau of Reclamation reports. Values are in km^3. Evaporation represent total estimated reservoir evaporation, Stock represents direct stock use and evaporation from stock ponds, SE represent thermoelectric generation cooling losses, Municipal represents municipal, rural domestic, and industrial consumption. Data are not publically available after 2005.
(http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html)

Year	*Total*	*Evaporation*	*Exports*	*Irrigation*	*Stock*	*Mining*	*SE*	*Municipal*
1971	12.71	1.56	5.71	4.75	0.11	0.08	0.04	0.44
1972	13.39	1.54	5.94	5.13	0.11	0.10	0.06	0.50
1973	13.21	1.70	5.66	5.05	0.12	0.10	0.06	0.53
1974	14.15	1.77	6.13	5.42	0.12	0.09	0.07	0.56
1975	13.51	1.66	5.50	5.50	0.11	0.09	0.07	0.56
1976	12.71	1.78	5.35	4.81	0.08	0.10	0.05	0.53
1977	13.16	1.67	5.39	5.32	0.08	0.09	0.05	0.56
1978	12.88	1.65	5.12	5.29	0.08	0.09	0.05	0.60
1979	12.91	1.82	5.08	5.18	0.07	0.10	0.05	0.63
1980	13.29	1.96	5.19	5.28	0.08	0.08	0.05	0.65
1981	14.33	1.60	5.25	6.46	0.07	0.08	0.05	0.82
1982	12.47	1.48	4.74	5.21	0.06	0.10	0.05	0.83
1983	10.91	1.72	4.45	3.70	0.06	0.07	0.04	0.87
1984	12.84	1.58	5.29	4.88	0.05	0.08	0.05	0.91
1985	12.69	1.66	5.35	4.53	0.06	0.09	0.04	0.96
1986	11.83	1.70	5.46	3.58	0.06	0.11	0.09	0.83
1987	12.64	1.62	5.84	4.02	0.06	0.13	0.10	0.88
1988	13.30	1.47	6.15	4.39	0.05	0.14	0.14	0.96
1989	14.31	1.53	6.57	4.82	0.06	0.16	0.11	1.06
1990	14.01	1.52	6.68	4.32	0.05	0.18	0.13	1.12
1991	13.13	1.65	5.51	4.63	0.05	0.17	0.13	0.99
1992	12.13	1.26	5.03	4.51	0.05	0.17	0.13	0.98
1993	12.60	2.00	5.30	3.95	0.05	0.17	0.12	1.01
1994	13.41	1.65	5.77	4.62	0.05	0.17	0.13	1.03
1995	13.38	1.68	5.43	4.93	0.05	0.16	0.12	1.01
1996	13.70	1.95	5.82	4.49	0.06	0.17	0.14	1.09
1997	13.36	1.82	5.84	4.21	0.06	0.16	0.14	1.13
1998	12.73	1.55	5.57	4.11	0.06	0.17	0.14	1.14
1999	13.05	2.04	5.72	3.68	0.06	0.16	0.15	1.23
2000	13.17	2.02	5.63	3.82	0.06	0.17	0.16	1.31
2001	13.18	1.85	5.75	3.86	0.06	0.16	0.15	1.35
2002	13.32	1.72	5.82	4.00	0.06	0.16	0.15	1.40
2003	11.77	1.61	4.88	3.52	0.06	0.16	0.15	1.40
2004	11.57	1.52	4.75	3.52	0.05	0.16	0.15	1.42
2005	11.85	1.19	4.91	3.92	0.06	0.16	0.15	1.46
Mean	12.48	1.65	5.29	3.77	0.06	0.16	0.15	1.39
Min	10.91	1.19	4.45	3.52	0.05	0.07	0.04	0.44
Max	14.33	2.04	6.68	6.46	0.12	0.18	0.16	1.46

Table S9a. Estimated TWS (TWSe) based on soil moisture storage from GLDAS and NLDAS LSM means and reservoir storage (RESS) for the UCRB. Rates of storage depletion and total volumes are provided for the major droughts and the net change for the entire record (1980 – 2014).

Value	*Interval and Duration (yr)*	*Slope (km^3/yr)*						*Total Volume (km^3)*					
		Noah	*MOS*	*VIC*	*CLM*	*Mean*	*STD*	*Noah*	*MOS*	*VIC*	*CLM*	*Mean*	*STD*
1990s drought													
TWSe GLDAS	05/86-05/90 (4.0)	-10.6	-9.0	-6.1	-4.9	**-7.6**	2.6	-42.9	-36.3	-24.5	-19.7	**-30.9**	10.7
TWSe NLDAS	05/86-05/90 (4.0)	-8.4	-6.6	-10.8	-	-8.6	2.1	-34.1	-26.9	-43.5	-	-34.8	8.3
SMS GLDAS	05/86-05/90 (4.0)	-8.2	-6.6	-3.6	-2.5	**-5.2**	2.6	-33.1	-26.6	-14.7	-9.9	**-21.1**	10.7
SMS NLDAS	05/86-05/90 (4.0)	-6.0	-4.2	-8.3	-	-6.2	2.1	-24.3	-17.1	-33.7	-	-25.0	8.3
RESS	03/89-11/92 (3.7)	-	-	-	-	-2.3	0.1	-	-	-	-	-8.7	0.5
2000s drought													
TWSe GLDAS	04/98-03/04 (5.9)	-10.4	-7.8	-4.7	-5.4	**-7.1**	2.5	-61.3	-46.1	-28.1	-32.2	**-41.9**	15.0
TWSe NLDAS	04/98-03/04 (5.9)	-6.3	-5.2	-6.9	-	-6.2	0.9	-37.6	-30.8	-40.9	-	-36.4	5.2
SMS GLDAS	04/98-03/02 (3.9)	-8.1	-4.8	-1.4	-2.8	**-4.3**	2.9	-31.7	-18.8	-5.5	-10.8	**-16.7**	11.4
SMS NLDAS	04/98-03/02 (3.9)	-4.7	-3.0	-5.6	-	-4.4	1.4	-18.6	-11.6	-22.0	-	-17.4	5.3
RESS	01/00-11/04 (4.8)	-	-	-	-	-4.1	0.1	-	-	-	-	-19.8	0.4
2010s drought													
TWSe GLDAS	05/11-03/13 (1.8)	-18.9	-15.9	-10.3	-13.0	-14.5	3.7	-34.8	-29.2	-18.9	-24.0	-26.7	6.8
TWSe NLDAS	05/11-03/13 (1.8)	-18.6	-15.4	-24.2	-	-19.4	4.5	-34.1	-28.2	-44.5	-	-35.6	8.2
SMS GLDAS	05/11-03/13 (1.8)	-11.1	-8.0	-2.5	-5.2	-6.7	3.7	-20.4	-14.8	-4.5	-9.6	**-12.3**	6.8
SMS NLDAS	05/11-03/13 (1.8)	-10.7	-7.5	-16.4		-11.6	4.5	-19.7	-13.8	-30.1	-	-21.2	8.2
RESS	11/11-11/13 (2.0)	-	-	-	-	-5.4	0.2	-	-	-	-	-10.8	0.4
1980-2014 reference period													
TWSe GLDAS	01/80-11/14 (35)	-1.4	-1.3	-1.0	-0.7	-1.1	0.3	-47.5	-44.8	-33.8	-23.7	**-37.5**	10.9
TWSe NLDAS	01/80-11/14 (35)	-0.6	-0.6	-0.6	-	-0.6	0.1	-19.8	-19.4	-22.7	-	-20.6	1.8
SMS GLDAS	01/80-11/14 (35)	-0.9	-0.8	-0.5	-0.2	-0.6	0.3	-31.8	-29.1	-18.1	-8.0	-21.8	10.9
SMS NLDAS	01/80-11/14 (35)	-0.1	-0.1	-0.2		-0.1	0.1	-4.1	-3.7	-7.0		-4.9	1.8
RESS	01/80-11/14 (35)	-	-	-	-	-0.5	0.0	-	-	-	-	-17.4	0.8

STD: standard deviation

Table S9b. Estimated TWS (TWSe) based on soil moisture storage from GLDAS and NLDAS LSM means, reservoir storage (RESS), and groundwater storage based on monitored water level data for the LCRB. Rates of storage depletion and total volumes are provided for the major droughts and the net change for the entire record (1980 – 2014).

Value	*Interval and Duration (yr)*	*Slope (km^3/yr)*						*Net change (km^3)*					
		Noah	*MOS*	*VIC*	*CLM*	*Mean*	*STD*	*Noah*	*MOS*	*VIC*	*CLM*	*Mean*	*STD*
1990s drought													
TWSe GLDAS	05/85-12/89 (4.6)	-17.2	-15.7	-12.7	-9.6	**-13.8**	3.4	-78.9	-72.0	-58.1	-43.9	**-63.2**	15.5
TWSe NLDAS	05/85-12/89 (4.6)	-11.4	-11.4	-13.8	-	-12.2	1.4	-52.3	-52.4	-63.4	-	-56.0	6.4
SMS GLDAS	05/85-12/89 (4.6)	-9.0	-7.5	-4.4	-1.3	**-5.6**	3.4	-41.1	-34.3	-20.3	-6.2	**-25.5**	15.5
SMS NLDAS	05/85-12/89 (4.6)	-3.2	-3.2	-5.6	-	-4.0	1.4	-14.5	-14.7	-25.6	-	-18.3	6.4
RESS	01/88-08/91 (3.6)	-	-	-	-	-2.3	0.1	-	-	-	-	**-8.2**	0.3
GW(obs)	1986-1990(4.0)	-	-	-	-	-9.3	1.1	-	-	-	-	**-37.3**	4.5
2000s drought													
TWSe GLDAS	04/98-04/04 (6.0)	-13.8	-11.4	-7.5	-7.4	**-10.0**	3.1	-82.7	-68.4	-45.3	-44.7	**-60.3**	18.6
TWSe NLDAS	04/98-04/04 (6.0)	-9.2	-8.2	-10.8	-	-9.4	1.3	-55.4	-49.2	-64.8	-	-56.4	7.8
SMS GLDAS	04/98-07/02 (4.3)	-8.7	-5.9	-1.3	-1.4	**-4.3**	3.6	-37.2	-25.0	-5.6	-5.8	**-18.4**	15.5
SMS NLDAS	04/98-07/02 (4.3)	-4.5	-2.8	-7.1	-	-4.8	2.2	-19.2	-11.8	-30.1	-	-20.4	9.2
RESS	12/99-07/04 (4.6)	-	-	-	-	-3.1	0.1	-	-	-	-	-14.0	0.3
GW(obs)	2002-2005(3.0)	-	-	-	-	-10.9	0.8	-	-	-	-	-32.7	2.3
2010s drought													
TWSe GLDAS	02/10-03/13 (3.1)	-4.2	-3.9	-2.1	-1.8	-3.0	1.2	-12.8	-11.9	-6.5	-5.5	-9.2	3.7
TWSe NLDAS	02/10-03/13 (3.1)	-6.3	-6.1	-5.8	-	-6.1	0.2	-19.3	-18.7	-18.0	-	-18.7	0.7
SMS GLDAS	02/10-03/13 (3.1)	-3.9	-3.6	-1.9	-1.6	-2.8	1.2	-12.1	-11.2	-5.8	-4.8	-8.5	3.7
SMS NLDAS	02/10-03/13 (3.1)	-6.0	-5.9	-5.6	-	-5.8	0.2	-18.6	-18.0	-17.3	-	-18.0	0.7
RESS	12/11-11/14 (2.9)	-	-	-	-	-1.9	0.1	-	-	-	-	-5.6	0.2
GW(obs)	2012-2014(2.0)	-	-	-	-	-7.1	0.7	-	-	-	-	-14.1	1.4
1980-2014 reference period													
TWSe GLDAS	01/80-11/14 (35)	-3.5	-3.4	-2.7	-2.1	-2.9	0.6	-121.5	-119.4	-96.0	-74.5	**-102.8**	22.2
TWSe NLDAS	01/80-11/14 (35)	-2.5	-2.3	-2.7	-	-2.5	0.2	-86.2	-81.8	-94.3	-	-87.4	6.5
SMS GLDAS	01/80-11/14 (35)	-1.5	-1.5	-0.8	-0.2	-1.0	0.6	-53.8	-51.6	-28.3	-6.8	-35.1	22.2
SMS NLDAS	01/80-11/14 (35)	-0.5	-0.4	-0.8	-	-0.6	0.2	-18.5	-14.0	-26.5	-	-19.7	6.3
RESS	01/80-11/14 (35)	-	-	-	-	-0.6	0.0	-	-	-	-	-20.2	0.5
GW(obs)	1980-2014(35.0)	-	-	-	-	-1.4	0.2	-	-	-	-	-48.2	7.8

Table S10. Identification numbers, locations, depths, and elevations of groundwater wells shown in Figure S17. Hydrographs are shown in Figure S18. (http://waterdata.usgs.gov/nwis)

Map Reference	*USGS Site ID*	*State*	*County*	*Aquifer*	*Well Depth (m)*	*Elevation (m)*
1	362936109564101	AZ	Apache	Navajo SS	259	1787
2	364338110154601	AZ	Navajo	Navajo SS	265	1745
3	393743106171000	CO	Eagle	Valley Fill	7	2598
4	383232106554700	CO	Gunnison	Valley Fill	7	2341
5	371422107473301	CO	La Plata	Alluvium/Terrace	34	2134
6	370410108583701	CO	Montezuma	Dakota SS	76	1494
7	394559108114201	CO	Rio Blanco	Green River Fm	331	2088
8	354235108170702	NM	McKinley	Westwater/Morrison Fm	678	2060
9	364220108054501	NM	San Juan	Alluvium	13	1646
10	393249110251501	UT	Carbon	Alluvium	20	1902
11	400945110240301	UT	Duchesne	Uinta Fm	33	1681
12	383158109282401	UT	Grand	Glen Canyon Fm	137	1414
13	375243109191301	UT	San Juan	Dakota SS	97	2108
14	373604109284301	UT	San Juan	(unknown)	48	1804
15	402654109334201	UT	Uintah	(unknown)	7	1657
16	381940111253501	UT	Wayne	(unknown)	34	2099
17	423539109382201	WY	Sublette	Farson/Green River Fm	45	2215
18	413850109150601	WY	Sweetwater	(unknown)	73	1960

Table S11. Water level changes during selected periods for groundwater wells in the Arizona AMA regions. Trends are categorized by mean annual water level change rates, defined as declining (< -1.0 ft/yr, 0.3 m/yr), rising (> 1.0 ft/yr, 0.3 m/yr), or otherwise (quasi-) stable. Periods represent water year intervals (Oct 1 – Sep 30). Wells were included that had ≥ 3 measurements during a given period with trend regression $r^2 \geq 0.5$. (https://gisweb.azwater.gov/waterresourcedata/gwsi.aspx)

AMA	*Period*	*Total Wells*	*Declining*			*Stable*			*Rising*		
			Wells	*% of wells*	*% of area*	*Wells*	*% of wells*	*% of area*	*Wells*	*% of wells*	*% of area*
Phoenix	1995-1999	134	54	40	40	32	24	26	48	36	34
	2000-2004	169	74	44	43	48	28	34	47	28	23
	2005-2010	243	38	16	18	53	22	28	152	63	55
	2011-2014	264	111	42	40	52	20	26	101	38	34
Pinal	1995-1999	71	12	17	16	12	17	19	47	66	65
	2000-2004	78	39	50	44	11	14	17	28	36	39
	2005-2010	95	29	31	31	8	8	8	58	61	62
	2011-2014	86	31	36	34	19	22	27	36	42	39
Prescott	1995-1999	16	13	81	86	3	19	14	0	0	0
	2000-2004	68	56	82	76	12	18	24	0	0	0
	2005-2010	72	54	75	57	12	17	28	6	8	14
	2011-2014	64	44	69	67	18	28	29	2	3	4
Santa Cruz	1995-1999	22	10	45	42	8	36	43	4	18	15
	2000-2004	15	10	67	62	4	27	28	1	7	10
	2005-2010	20	5	25	17	9	45	62	6	30	21
	2011-2014	25	18	72	62	5	20	28	2	8	10
Tucson	1995-1999	376	280	74	51	62	16	34	34	9	15
	2000-2004	505	317	63	47	46	9	25	142	28	28
	2005-2010	531	96	18	30	68	13	26	367	69	44
	2011-2014	82	46	56	47	21	26	33	15	18	20

Table S12. GRACE TWS trends and net volume changes in the UCRB and LCRB based on different models

Value	*Model*	*UCRB 04/2011 – 03/2013 (1.8 yr duration)*	*LCRB 02/2010 – 03/2013 (3.1 yr duration)*
Slope (km^3/yr)	CSR gridded	-20.3	-10.7
	GFZ gridded	-18.7	-9.0
	JPL gridded	-20.4	-9.0
	CSR basin	-19.8	-9.5
	CSR Mascons	-14.8	-6.5
	Mean	-18.8	-6.9
	Standard deviation	2.3	1.5
Net change (km^3)	CSR gridded	-37.3	-33.1
	GFZ gridded	-34.4	-27.6
	JPL gridded	**-37.4**	-27.9
	CSR basin	-36.3	-29.2
	CSR Mascons	**-27.2**	**-20.0**
	Mean	-34.5	-27.6
	Standard deviation	4.3	4.7

Table S13a. GRACE groundwater regression slope and net volume change results based on the GLDAS and NLDAS models for 05/2011 – 03/2013 (1.8 yr) time period in the UCRB.

Value	*Slope (km³/yr)*						*Net change (km³)*					
	Noah	*MOS*	*VIC*	*CLM*	*Mean*	*STD*	*Noah*	*MOS*	*VIC*	*CLM*	*Mean*	*STD*
GWS (TWS – **GLDAS** – SnWS – RESS)												
CSR gridded	-1.4	-4.4	-10.0	-7.3	-5.8	3.7	-2.6	-8.2	-18.4	-13.4	-10.6	6.8
GRZ gridded	0.2	-2.8	-8.4	-5.7	-4.2	3.7	0.4	-5.2	-15.4	-10.4	-7.7	6.8
JPL gridded	-1.4	-4.5	-10.0	-7.3	-5.8	3.7	-2.6	-8.2	-18.4	-13.4	-10.7	6.8
CSR basin	-0.8	-3.9	-9.5	-6.7	-5.2	3.7	-1.5	-7.1	-17.3	-12.3	-9.6	6.8
CSR Mascons	4.1	1.1	-4.5	-1.8	-0.3	3.7	7.6	2.0	-8.2	-3.2	**-0.5**	6.8
Mean	0.1	-2.9	-8.5	-5.7	-4.3	3.7	0.3	-5.3	-15.6	-10.5	-7.8	6.8
GWS (TWS – **NLDAS** – SnWS – RESS)												
CSR gridded	-1.7	-5.0	3.9	-	-0.9	4.5	-3.2	-9.1	7.2	-	-1.7	8.2
GRZ gridded	-0.1	-3.4	5.5	-	0.7	4.5	-0.3	-6.2	10.1	-	1.2	8.2
JPL gridded	-1.8	-5.0	3.9	-	-1.0	4.5	-3.3	-9.2	7.1	-	-1.8	8.2
CSR basin	-1.2	-4.4	4.5	-	-0.4	4.5	-2.2	-8.1	8.2	-	-0.7	8.2
CSR Mascons	3.8	0.6	9.4	-	4.6	4.5	6.9	1.0	17.3	-	8.4	8.2
Mean	-0.2	-3.4	5.4	-	0.6	4.5	-0.4	-6.3	10.0	-	1.1	8.2

Table S13b. GRACE groundwater regression slope and net volume change results based on the GLDAS and NLDAS models for 02/2010 – 03/2013 (3.1 yr) time period in the LCRB. Bounding estimates of GWS are based on low TWS – high SMS (highlighted in blue) and high TWS and low SMS (highlighted in red).

Value	*Slope (km³/yr)*						*Total change (km³)*					
	Noah	*MOS*	*VIC*	*CLM*	*Mean*	*STD*	*Noah*	*MOS*	*VIC*	*CLM*	*Mean*	*STD*
GWS (TWS – **GLDAS** – SnWS – RESS)												
CSR gridded	-7.8	-8.1	-9.9	-10.2	-9.0	1.2	-24.1	-25.0	-30.5	**-31.5**	-27.8	3.7
GRZ gridded	-6.1	-6.4	-8.1	-8.4	-7.2	1.2	-18.7	-19.6	-25.0	-26.0	-22.3	3.7
JPL gridded	-6.1	-6.4	-8.2	-8.5	-7.3	1.2	-18.9	-19.8	-25.3	-26.3	-22.6	3.7
CSR basin	-6.6	-6.9	-8.6	-9.0	-7.8	1.2	-20.2	-21.1	-26.6	-27.6	-23.9	3.7
CSR Mascons	-3.6	-3.9	-5.7	-6.0	-4.8	1.2	**-11.1**	-12.0	-17.4	-18.4	-14.7	3.7
Mean	-6.0	-6.3	-8.1	-8.4	-7.2	1.2	-18.6	-19.5	-24.9	-25.9	-22.3	3.7
GWS (TWS – **NLDAS** – SnWS – RESS)												
CSR gridded	-5.7	-5.9	-6.2	-	-5.9	0.2	-17.7	-18.2	**-19.0**	-	-18.3	0.7
GRZ gridded	-4.0	-4.1	-4.4	-	-4.2	0.2	-12.2	-12.8	-13.5	-	-12.9	0.7
JPL gridded	-4.1	-4.2	-4.5	-	-4.3	0.2	-12.5	-13.0	-13.8	-	-13.1	0.7
CSR basin	-4.5	-4.7	-4.9	-	-4.7	0.2	-13.8	-14.3	-15.1	-	-14.4	0.7
CSR Mascons	-1.5	-1.7	-1.9	-	-1.7	0.2	**-4.7**	-5.2	-6.0	-	-5.3	0.7
Mean	-4.0	-4.1	-4.4	-	-4.2	0.2	-12.2	-12.7	-13.5	-	-12.8	0.7
GW (measurements 2012-2014)												
GW (obs)					-7.1	0.7					-14.1	1.4

Table S14. Summary of synoptic ground-based gravity measurements water storage changes (ΔS) in the Phoenix AMA and Pinal AMA regions. Measurement locations and analytical areas are shown in Figure S4.

Survey Date	*Increment (yr)*	*Cumulative (yr)*	*Cumulative ΔS (km^3)*	*Incremental Rate (km^3/yr)*	*Cumulative Rate (km^3/yr)*
Phoenix AMA					
4/12/2002	0	0	-	0	0
4/4/2003	1.0	1.0	0.38	0.39	0.39
5/12/2004	1.1	2.1	0.55	0.16	0.26
5/3/2005	1.0	3.1	2.34	1.84	0.77
5/8/2007	2.0	5.1	1.62	(0.36)	0.32
6/23/2009	2.1	7.2	**2.44**	0.39	**0.34**
Pinal AMA					
1/1/1999	0	0	-	0	0
1/14/2000	1.0	1.0	0.45	0.44	0.44
1/25/2001	1.0	2.1	0.48	0.02	0.23
1/22/2002	1.0	3.1	0.15	(0.33)	0.05
1/19/2003	1.0	4.1	1.30	1.16	0.32
12/25/2005	2.9	7.0	1.42	0.04	0.20
1/30/2008	2.1	9.1	**2.36**	0.45	**0.26**
1/1/2014	5.9	15.0	**1.69**	(0.11)	**0.11**

Table S15. Water-level changes in wells and gravity-based storage change in the Phoenix and Pinal AMA regions. Periods are determined by major periods of gravity-based storage change, 2000 to 2005 and 2007-2009 in the Phoenix AMA and 1999-2008 and 2008-2014 in the Pinal AMA. Trends are categorized by mean-annual change rates, defined for water-level change as declining (< -0.3 m/yr), rising (> 0.3 m/yr), or otherwise stable with an r^2 >0.40 and for gravity-based storage change as declining (< -0.1.5 m/yr), rising (> 0.15 m/yr). Water-level records include data for 1 year before and 1 year following the average date of the gravity survey. Gravity trends were primarily calculated as the difference of two surveys divided by the number of years between surveys, except for the period 1999-2008 in the Pinal AMA, which was calculated as the average linear trend of several surveys. (https://gisweb.azwater.gov/waterresourcedata/gwsi.aspx)

AMA	*Period*	*Total Wells*	*Declining Wells*	*Stable Wells*	*Rising Wells*
Water level trends					
Phoenix	2001-2004	108	55	7	46
	2006-2010	199	57	8	134
Pinal	2000-2009	43	20	5	18
	2008-2014	118	38	21	59
Gravity-based storage trends					
Phoenix	2002-2004	78	27	6	33
	2007-2009	61	23	4	31
Pinal	1999-2008	95	8	17	70
	2008-2014	64	30	8	26

Table S16. Correlations of gravity-based storage change and water-level trends for selected periods in the Phoenix and Pinal AMAs. Records of storage change at gravity stations in the Phoenix AMA were paired with water-level records at wells within 4 km of the gravity station. Records of storage change at gravity stations in the Pinal AMA were paired with water-level records at wells within 1 km of the gravity station. Trends are categorized by mean-annual change rates, defined for water-level change as declining (< -0.3 m/yr), rising (> 0.3 m/yr), or otherwise stable with an r^2 >0.40 and for gravity-based storage change as declining (< -0.1.5 m/yr), rising (> 0.15 m/yr). Water-level records include data for 1 year before and 1 year following the average date of the gravity survey. Gravity trends were primarily calculated as the difference of two surveys divided by the number of years between surveys, except for the period 2000-2008 in the Pinal AMA, which was calculated as the average linear trend of several surveys.

a) Water-level trends near gravity stations					
AMA	*Period*	*Total Wells*	*Declining Wells*	*Stable Wells*	*Rising Wells*
Phoenix	2001-2004	44	25	4	15
	2006-2010	51	10	5	36
Pinal	1999-2008	22	7	2	13
	2008-2014	40	7	3	30

b) Gravity-based storage trends at stations near wells with water-level records					
AMA	*Period*	*Total Stations*	*Declining Stations*	*Stable Stations*	*Rising Stations*
Phoenix	2001-2004	44	7	16	21
	2006-2010	37	9	10	18
Pinal	1999-2008	22	11	4	7
	2008-2014	44	18	6	20

c) Estimates of storage change source from correlation of gravity-based storage trends and water-level trends at nearby wells						
AMA	*Period*	*Total gravity station/well pairs*	*Positive correlation and SY estimates*	*Local confined aquifer*	*Storage change in shallow aquifers or the unsaturated zone*	*Insufficient change In gravity and water levels*
Phoenix	2001-2004	44	10	16	14	4
	2006-2010	51	16	1	33	1
Pinal	1999-2008	22	9	2	5	6
	2008-2014	40	23	6	11	0

References

Landerer, F. W., and S. C. Swenson (2012), Accuracy of scaled GRACE terrestrial water storage estimates, *Water Resources Research*, *48*.

Maupin, M. A., J. F. Kenny, S. S. Hutson, J. K. Lovelace, N. L. Barber, and K. S. Linsey (2014), Estimated use of water in the United States in 2010, *U.S. Geol. Surv. Circular 1405, 56 p.*

Rodell, M., I. Velicogna, and J. S. Famiglietti (2009), Satellite-based estimates of groundwater depletion in India, *Nature*, *460*(7258), 999-U980.

Rowlands, D. D., S. B. Luthcke, J. J. McCarthy, S. M. Klosko, D. S. Chinn, F. G. Lemoine, J. P. Boy, and T. J. Sabaka (2010), Global mass flux solutions from GRACE: A comparison of parameter estimation strategies-Mass concentrations versus Stokes coefficients, *Journal of Geophysical Research-Solid Earth*, *115*.

Save, H., S. Bettadpur, and B. D. Tapley (2012), Reducing errors in the GRACE gravity solutions using regularization, *Journal of Geodesy*, *86*(9), 695-711.

Save, H., S. Bettadpur, and B. D. Tapley (2015), Evaluation of global equal-area mass grid solutions from GRACE, European Geosciences Union General Assembly, Vienna, Austria 2015.

Swenson, S., and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data, *Geophysical Research Letters*, *33*(8).

Tillman, F. D., and S. A. Leake (2010), Trends in groundwater levels in wells in the active management areas of Arizona, USA, *Hydrogeology Journal*, *18*(6), 1515-1524.