ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL115593

Declining Freshwater Availability in the Colorado River Basin Threatens Sustainability of Its Critical Groundwater Supplies

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Key Points:

- Groundwater depletion accounted for 53% of TWS loss in the UCRB and 71% in the LCRB, far greater than the losses in Lakes Powell and Mead
- Groundwater management practices and access to surface water have reduced depletion rates in managed areas of the LCRB compared to unmanaged regions
- Expansion of groundwater management and inclusion of groundwater in interstate water discussions may help chart a path to sustainability

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Abdelmohsen, K., Famiglietti, J. S., Ao, Y. Z., Mohajer, B., & Chandanpurkar, H. A. (2025). Declining freshwater availability in the Colorado River basin threatens sustainability of its critical groundwater supplies. *Geophysical Research Letters*, *52*, e2025GL115593. https://doi.org/10.1029/2025GL115593

Received 3 MAR 2025
Accepted 9 MAY 2025

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Abstract

The Colorado River Basin (CRB) is experiencing persistent aridification due to a complex interplay of natural and anthropogenic activities, resulting in significant groundwater depletion across the region. We used over two decades of NASA GRACE and GRACE Follow-On (GRACE-FO) observations (April 2002–October 2024), land surface models and observed data, to document pronounced groundwater depletion in the CRB. We estimate that the CRB lost 52.2 ± 4.0 km^3 of terrestrial water storage over the study period, of which groundwater accounted for 65% (34.3 ± 9.2 km^3). Of this, the Upper Basin lost 14.6 ± 3.5 km^3 of terrestrial water storage (53% from groundwater, 7.8 ± 5.3 km^3) while the Lower Basin lost 36.0 ± 6.2 km^3 of terrestrial water storage (71% from groundwater, 25.5 ± 7.4 km^3). Progress toward groundwater sustainability could be achieved by reducing annual extraction in line with the annual depletion rates presented here (0.35 km^3/yr in Upper Basin and 1.15 km^3/yr in the Lower Basin).

Plain Language Summary

Climate change is causing more frequent and intense droughts around the world, including in the Colorado River Basin, which supplies water to seven U.S. states and Mexico, and is facing severe water shortages. This study investigates how changes in water storage components (e.g., snow, surface water, soil moisture and groundwater) and water use are contributing to these shortages, and impacting agriculture and municipal water supplies, using data from the NASA GRACE and GRACE Follow-On (GRACE-FO) satellite missions, land surface models, and in situ data over the past two decades. Results show significant losses of groundwater: 7.8.0 ± 5.3 km^3 in the Upper CRB (UCRB) and 25.5 ± 7.4 km^3 in the Lower CRB (LCRB). Progress toward sustainable groundwater could be achieved by reducing groundwater extraction, in line with current rates of depletion (0.35 km^3 in the UCRB and 1.15 km^3 in the LCRB). This research highlights the importance of understanding the factors affecting groundwater levels to create sustainable water management strategies that can help secure water resources for the region's future.

1. Introduction

The Colorado River Basin (CRB), located in the southwestern United States, is facing unprecedented water management challenges due to the impacts of climate change, including severe aridification and increasing variability in the water cycle (Allan et al., 2020; Dettinger et al., 2015; Tran et al., 2022). Over the past century, the region has experienced a temperature increase of approximately 0.8°C, leading to significant reductions in freshwater availability (Bolinger et al., 2024; Dettinger et al., 2015; Gangopadhyay et al., 2022; Pokharel et al., 2022; Stone et al., 2023; Udall & Overpeck, 2017). Previous analyses using NASA's Gravity Recovery and Climate Experiment (GRACE) mission documented significant groundwater depletion between 2004 and 2013 (Castle et al., 2014; Scanlon et al., 2015). Projections for the future suggest that this depletion will continue, with more frequent and prolonged droughts exacerbating the already critical water shortage in the region (Condon et al., 2020; McCabe & Wolock, 2007; Strzepek et al., 2010; Whitney et al., 2023).

As Colorado River streamflow diminishes, the reliability of surface water resources has become increasingly threatened. Over the past century, the river's flow has decreased by approximately 20%, and climate models predict further reductions of up to 30% by mid-century due to rising temperatures and reduced snowpack in the Rocky Mountains, which feed the river (Udall & Overpeck, 2017; Milly & Dunne, 2020; Whitney et al., 2023). Although all seven states have equal priority under the 1922 Colorado River Compact, Arizona is particularly

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vulnerable to water shortages because, under the 2007 Interim Guidelines, it faces the largest mandatory reductions in water deliveries when Lake Mead reaches critically low elevations (Bureau of Reclamation, 2020). Arizona, which represents a substantial portion of the LCRB in terms of land area and water use, faces the possibility of significant water cutbacks, potentially losing up to 512 million cubic meters (approximately 415,000 acre-feet) of its annual allotment if water levels in Lake Mead continue to decline (Bureau of Reclamation, 2020). The decline of the river poses a severe threat to both agricultural and municipal water supplies, which are heavily reliant on the river. Approximately 80% of the CRB's water is used for irrigation (Richter et al., 2020), supporting a $1.4 billion agricultural industry in Arizona alone (Department of Agriculture, 2017).

This situation places immense pressure on the region's groundwater resources. As surface water becomes less dependable, the demand for groundwater is projected to rise significantly (Liu et al., 2022; McCabe & Wolock, 2007; Tillman et al., 2020). In the Lower Colorado River Basin (LCRB), groundwater already accounts for approximately 40% of the total water supply, with usage expected to increase as surface water availability declines (Bureau of Reclamation, 2012). However, the lack of robust protection and management strategies for groundwater in the CRB puts these resources at significant risk of over-exploitation. Groundwater is a crucial buffer as water supply in arid environments like the LCRB, but it is rapidly disappearing due to excessive extraction on one hand and insufficient recharge and management on the other. Previous studies (Castle et al., 2014; Scanlon et al., 2015) have documented signiflcant groundwater losses and corresponding falling groundwater levels in the LCRB between 2003 and 2014.

In this study, we utilize NASA GRACE and GRACE Follow-On (GRACE-FO) satellite observations of terrestrial water storage (TWS; all of the snow, ice, surface water, soil moisture and groundwater (Syed et al., 2010)), combined with land surface models and in situ data, to quantify groundwater depletion in the CRB. (Hereafter we refer to the combinded GRACE and GRACE-FO data set as GRACE/FO). We estimate significant losses in TWS, particularly in the groundwater component, across both the Upper CRB (UCRB) and LCRB. Our groundwater storage variation (GWS) estimates were derived from GRACE/FO, using outputs from the North American Land Data Assimilation System (NLDAS) (Mitchell et al., 2004), the Snow Data Assimilation System (SNODAS) (National Operational Hydrologic Remote Sensing Center, 2004), and Surface Water Reservoir Storage (SWRS), including 47 reservoirs in the Colorado River Basin (U.S. Bureau of Reclamation; www.usbr.gov/UC/ or/LC and private entities), and revealed critical losses in groundwater storage. These findings underscore that reducing annual groundwater extraction can help mitigate ongoing losses. Furthermore, they highlight the urgent need for sustainable water management practices to secure the long-term availability of groundwater resources in this increasingly vulnerable region.

2. Data and Methods

For this analysis three GRACE/FO mascon solutions were utilized and reported relative to a 2004–2009 mean baseline: the NASA Jet Propulsion Laboratory (JPL-RL06.1M), the University of Texas Center for Space Research (CSR-RL0602M) and NASA Goddard Space Flight Center (GSFC-RL06v2.0M) (Loomis et al., 2019; H. Save, 2019; Watkins et al., 2015; Wiese et al., 2016) (Figure S1 in Supporting Information S1). The CSR-RL0602M oversampled on an equiangular grid of size 0.25° × 0.25°(Save, 2020). No post-processing and/or filtering or application of empirical scaling factors was applied (Save et al., 2016).

To assess the accuracy of GRACE data estimates in both the UCRB and LCRB, we conducted an independent water mass balance analysis using hydrological fluxes from three models (NOAH, VIC and Mosaic) from NLDAS (Mitchell et al., 2004), including precipitation (P), evapotranspiration (ET), and total runoff (Q) (Equation 1; Figures S2 and S3 in Supporting Information S1) (Rodell, Famiglietti et al., 2004; Rodell, Houser et al., 2004).

$$\frac{\Delta S}{\Delta t} = P - \mathrm{ET} - Q \qquad (1)$$

Change in water storage over time is $\Delta S/\Delta t$, P includes both liquid and solid precipitation, ET is total evapotranspiration, and Q represents total runoff (comprising surface and subsurface flows). All the hydrological fluxes were estimated as the mean of the three models outputs. The difference between the input (P) and the outputs (ET and Q) is equal to the change in water storage ($\Delta S/\Delta t$), which can also be computed as the temporal derivative of GRACE-based terrestrial water storage anomalies (GRACE/FO $\Delta S/\Delta t$).

Annual and Monthly Precipitation data for the CRB were derived from the Climate Hazards Center InfraRed Precipitation with Station (CHIRPS) precipitation data set (Funk et al., 2015) (Figure S4 in Supporting Information S1). The CHIRPS data are an integration of different satellite imagery with gauge stations data at spatial resolution of 0.05° (Funk et al., 2015). CHIRPS version 2.0 data are available at (https://data.apps.fao.org/catalog/organization/chirps).

We quantified the temporal variations in SWRS across the CRB by utilizing the measured change in water volume in 47 reservoirs, including Lakes Powell and Mead (Castle et al., 2014; Scanlon et al., 2015), which account for most of its surface water storage (Bureau of Reclamation: www.usbr.gov/UC/ or/LC and private entities) (Figure S13 in Supporting Information S1).

The GRACE/FO TWS and outputs of NLDAS and SNODAS models were used to derive the variations in groundwater storage (Rodell et al., 2007, 2009; Rodell & Famiglietti, 2002; Yeh et al., 2006). The NLDAS models provide Soil Moisture Storage (SMS), and SNODAS provides Snow Water Equivalent (SWE). The GRACE/FO-derived GWS time series (GWS) were calculated by subtracting modeled NLDAS SMS (SMS), SNODAS SWE (SWE), and the measured SWRS from GRACE/FO TWS (TWS_{GRACE}, Equation 2 (Rodell & Famiglietti, 2002) (Figure S6 in Supporting Information S1).

$$GWS = TWS_{GRACE} - SMS - SWE - SWRS \tag{2}$$

The wells distributed in the unconfined aquifers of the LCRB were utilized in these study. 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). No observational data were available for deeper wells in confined aquifers, so that a complete view of groundwater storages changes from in situ well observations is not available. For detailed information on the criteria of processing and analysis the monitoring well data see Text S1 in Supporting Information S1.

Nonseasonal time series were utilized in the analysis to reduce the contribution of the seasonal mass to the trend calculations (Rodell et al., 2018). The nonseasonal time series components were calculated by removing the seasonal cycle using STL (Seasonal-Trend decomposition based on LOESS), which include the following steps: (a) filling in the missing months by utilizing linear interpolation, (b) applying STL decomposition to separate seasonal and trend components, and (c) extracting the nonseasonal (trend) component from the non-gap-filled time series (Abdelmohsen et al., 2019; Rodell et al., 2018). The non-seasonal time series were used to estimate the water volume of gains or losses in the basins. The analysis for the entire Basin (CRB) was conducted independently from the analyses of UCRB and LCRB, rather than simply summing the values from the two sub-basins, allows for a more comprehensive assessment of regional variations and aggregate trends within the CRB. The uncertainty in GRACE TWS is represented by the standard deviation among the three selected solutions (CSR-RL06M, JPL-RL06M, and GSFC-RL06v2.0M) (Scanlon et al., 2016). The uncertainty in the water mass balance estimates was determined by calculating the combined errors of all hydrological fluxes in quadrature, following the approach of (Rodell, Famiglietti et al., 2004; Rodell, Houser et al., 2004). Since no explicit error estimates are available for NLDAS precipitation data, we applied a 15% uncertainty to the measured storage changes (Jeton et al., 2005). The error margin for total Q was set at 5% (Rodell, Famiglietti et al., 2004; Rodell, Houser et al., 2004) while the uncertainty for ET was assumed to be 15% (Tang et al., 2009).

The error associated with the calculated SWRS was set at 15% of the measured storage since no error estimates for these measurements were found (Liu et al., 2022). The accuracy of SNODAS SWE has been reported to range from 10% to 20% at different basin scales (Artan et al., 2013; Bair et al., 2016; Clow et al., 2012). For our analysis, we assumed an uncertainty of 15% for SWE. SMS error analysis in Text S5 of Supporting Information S1 (Figures S10 and S14 in Supporting Information S1) (Castle et al., 2014).

Finally, the standard deviation of the derived time series was interpreted as the error for the calculated water mass values (e.g., SWRS and NLDAS SMS). The errors in GWS (σGWS) were calculated by adding, in quadrature, the estimated errors related to TWS, SWRS, SMS NLDAS and SWE SNODAS trends (Equation 3).

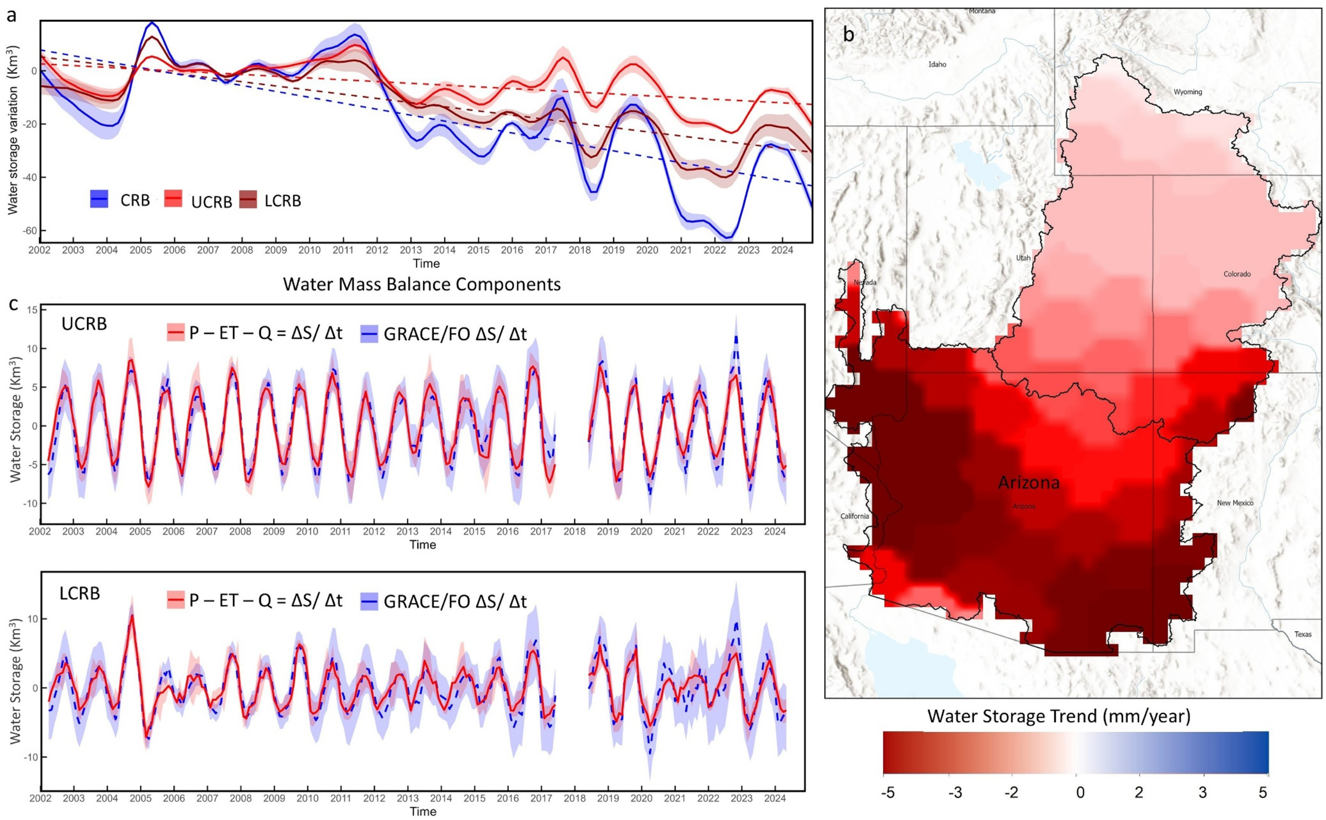

Figure 1. GRACE TWS trend map. (a) The time series of nonseasonal GRACE/FO TWS (km^3/year) over UCRB and LCRB for the period (4/2002–10/2024). (b) Spatial variation in TWS trends for the Colorado River Basin for the investigated period (mm/year) (c) Time series comparison of the change in storage $\Delta S/\Delta t$ derived from the water balance equation (Equation 1) and GRACE/FO. $\Delta S/\Delta t$ calculated from GRACE/FO TWS anomalies in km^3. The light shading represents uncertainties.

$$\sigma \mathrm{GWS}_{\mathrm{GRACE}} = \sqrt{\sigma \mathrm{TWS}^2_{\mathrm{GRACE}} + \sigma \mathrm{SWRS}^2_{\mathrm{ALT}} + \sigma \mathrm{SMS}^{\,2}_{\mathrm{NLDAS}} + \sigma \mathrm{SWE}^{\,2}_{\mathrm{SNODAS}}} \tag{3}$$

3. Results

The entire CRB experienced significant TWS loss as shown in Figures 1a and 1b and Table 1. The non-seasonal GRACE/FO TWS time series over the CRB shows significant variations throughout the study period, with a clear declining trend, indicating ongoing losses from storage. Overall, the CRB lost 52.2 ± 4 km^3 (2.37 ± 0.2 km^3/yr) of TWS between 2003 and 2024, of which the LCRB and UCRB lost 36.0 ± 6.2 km^3 (1.6 ± 0.3 km^3/yr) and 14.6 ± 3.5 km^3 (0.66 ± 0.2 km^3/yr), respectively (Figure 1 and Table 1).

The distribution of seasonal precipitation across the CRB is uneven, with higher seasonal precipitation intensity in the UCRB compared to the LCRB (average annual precipitation: 321 and 283 mm/yr, respectively) (Figure S4 in Supporting Information S1). In the LCRB, summer precipitation is driven by the North American Monsoon, while snow is largely confined to the UCRB due to its higher elevation. This disparity is reflected in the TWS seasonal cycle amplitude, with the UCRB showing an amplitude 1.5 times greater than the LCRB (Figure S4 in Supporting Information S1).

We computed the monthly change in storage (ΔS/Δt) based on the water balance equation (Equation 1) and compared these estimates with the GRACE/FO ΔS/Δt values by taking the difference in TWS anomalies between two consecutive months. The comparison shows a strong correlation between ΔS/Δt and GRACE/FO ΔS/Δt, with a root mean square error (RMSE) of 0.01, a Pearson correlation coefficient (r) of 0.9, and a Nash-Sutcliffe Efficiency Coefficient (E) of 0.8 for both the UCRB and LCRB (Figure 1c). As in the case of Castle et al. (2014), the close comparison between water balance and GRACE/FO estimates provides confidence that GRACE/FO is

Table 1
Partitioning of Water Components

Basin	Years	ΔTWS[a]			ΔSWRS[b]			ΔSMS[c]			ΔSWE[d]			ΔGWS[e]		
		(km^3)	(km^3/yr)	(mm/yr)	(km^3)	(km^3/yr)	(mm/yr)	(km^3)	(km^3/yr)	(mm/yr)	(km^3)	(km^3/yr)	(mm/yr)	(km^3)	(km^3/yr)	(mm/yr)
CRB	22	−52.2 ± 4.0	−2.37 ± 0.2	−3.6 ± 0.5	−14.4 ± 1.5	−0.65 ± 0.1	−1.0 ± 0.2	−5.8 ± 5.6	−0.26 ± 0.2	−0.41 ± 0.1	2.4 ± 0.3	0.1 ± 00	0.17 ± 00	−34.3 ± 9.2	−1.35 ± 0.4	−1.8 ± 0.9
UCRB	22	−14.6 ± 3.5	−0.66 ± 0.2	−2.27 ± 0.5	−5.3 ± 0.8	−0.24 ± 0.03	−0.84 ± 0.1	−3.8 ± 4.0	−0.17 ± 0.1	−0.6 ± 0.1	2.3 ± 0.3	0.1 ± 0.01	0.3 ± 00	−7.8 ± 5.3	−0.35 ± 0.2	−0.1 ± 0.5
LCRB	22	−36.0 ± 6.2	−1.6 ± 0.3	−4.67 ± 0.8	−8.8 ± 1.3	−0.4 ± 0.1	−1.2 ± 0.2	−1.76 ± 4.0	−0.08 ± 0.1	−0.23 ± 0.01	5×10^{-3} ± 00	2×10^{-4} ± 00	6×10^{-4} ± 00	−25.5 ± 7.4	−1.15 ± 0.3	−3.24 ± 0.8

Note. Partitioning of TWSGRACE, SWRS, SMSNLDAS, SWESNODAS and GWSGRACE trends over the CRB. GRACE observations, NLDAS, SNODAS outputs, and Reservoir measurements were used to estimate the partitioning of TWS in GWS. [a]ΔTWS: Change in terrestrial water storage. [b]ΔSWRS: Change in surface water reservoir storage over the primary main reservoirs. [c]Δ SMS: Change in soil moisture storage. [d]Δ SWE: Change in snow water equivalent. [e]ΔGWS: Change in groundwater storage.

representing actual storage changes well, and that they can be used with confidence to estimate GWS changes in the UCRB and LCRB.

The time series of GWS change for the CRB, the UCRB and the LCRB (Figure 2) were estimated using GRACE/FO TWS and outputs from NLDAS, SNODAS, and SWRS in a mass balance following Equation 3 (Rodell & Famiglietti, 2002). Different storage components, namely GWS, SWRS, SMS, and SWE, contribute to overall TWS temporal variations (Figure 2, right panel). The declining trend in groundwater storage is particularly pronounced, especially in the LCRB. Groundwater accounts for 65% of TWS loss across the CRB (34.3 ± 9.2 km^3; 1.55 ± 0.4 km^3/yr). In the UCRB, 53% of TWS loss is attributed to groundwater (7.8 ± 5.3 km^3; 0.35 ± 0.2 km^3/yr), and an even more substantial 71% (25.5 ± 7.4 km^3; 1.15 ± 0.3 km^3/yr) in the LCRB. The change in groundwater volume from monitoring wells located in unconfined aquifers in LCRB reveals a pronounced and consistent decline in the water table (black dashed line; Figure S12 in Supporting Information S1), which closely correlates with GRACE/FO GWS change, yielding an RMSE of 0.2 and r of 0.6. These data were obtained from the Arizona Department of Water Resources (ADWR; https://gisweb.azwater.gov/waterresourcedata/GWSI.aspx, accessed April 2024).

Lakes Mead and Powell continue to overwhelmingly dominate the total reservoir storage signal in the CRB. Surface water losses from CRB play a notable role, contributing 36% (5.3 ± 0.8 km^3; 0.24 ± 0.03 km^3/yr) toward TWS loss in the UCRB and 24% (8.8 ± 1.3 km^3; −0.4 ± 0.1 km^3/yr) in the LCRB. In contrast, SMS and SWE have a less impact, accounting for only 26% and −15% (SMS: 3.8 ± 4.0 km^3; 0.17 ± 0.1 km^3/yr; SWE: 2.3 ± 0.3 km^3; 0.1 ± 0.01 km^3/yr), where SWE counteracts 15% of the total TWS loss in the UCRB, and 5% (SMS: 1.76 ± 4.0 km^3; 0.08 ± 0.1 km^3/yr; SWE: 5×10^{-3} ± 0.0 km^3; 2×10^{-4} ± 0.0 km^3/yr) of TWS loss in the UCRB and LCRB, respectively.

Basin-wide, groundwater accounts for approximately 65% of total TWS loss across the CRB (34.3 ± 9.2 km^3 out of 52.2 ± 4.0 km^3), followed by surface water at 28% (14.4 ± 1.5 km^3), soil moisture at 11% (5.8 ± 5.6 km^3), and snow at −4% (2.31 ± 0.3 km^3). This component-based analysis highlights the critical importance of groundwater in the overall water balance, confirming it as the primary driver of long-term TWS declines in the CRB. This water storage component analysis highlights the critical importance of groundwater in the overall water balance and as the dominant reason for declining TWS in the CRB.

3.1. Geographic Differentiation of Water Use in the LCRB

Given the greater amount of TWS and GWS loss in the LCRB, we use data from the University of Arizona and the Arizona Department of Water Resources (ADWR, 2016) to geographically differentiate water use and losses across LCRB groundwater basins. We grouped groundwater basins (ADWR, 2021a) into the larger, aggregate groundwater basins shown in Figure 3a based on water usage or the existence of groundwater management: mostly surface water and surface water source (Central Arizona Project (CAP) or Colorado River (CR)); mostly groundwater; and Arizona's groundwater Active Management Areas (AMAs; where groundwater is managed according to a management plan (ADWR, 2021a)) and Irrigation Non-Expansion Areas (INAs; where expansion of irrigated land is prohibited (ADWR, 2021)). Table S2 in Supporting Information S1 outlines the groundwater basins that were combined to form the aggregated groundwater basins illustrated in Figure 3a. Figure 3b shows TWS changes in the corresponding groundwater basins. The LCRB groundwater basins in Figure 3 cover the majority of Arizona.

As shown in Figures 1 and 2, the entire CRB displays declining TWS and GWS. Figure 3 provides a more granular perspective, highlighting that groundwater basins which are primarily dependent on groundwater sources, that is, those with over 90% of their water supply drawn from groundwater (ADWR, 2022; Christiansen & Hamblin, 2023) (basins 1 and 2, shown in pink in Figure 3a) have greater TWS loss rates than those with access to surface water (basins 4, 5 and 6, shown in blue in Figure 3a). For example, basins 1 and 2 have TWS loss rates of 8.1 ± 1.3 and 7.3 ± 1 mm/year, respectively, with corresponding GWS depletion rates of 7.2 and 5.9 mm/year (see Table S3 in Supporting Information S1). Basin 1 includes the Douglas and Santa Cruz AMAs, which rely on groundwater for 90%–100% of their total water supply, while basin 2 encompasses the Prescott AMA and Hualapai Valley INA, where groundwater provides 80%–90% of water needs (ADWR, 2022; Christiansen & Hamblin, 2023). Despite some AMA and INA regions included within these basins, the groundwater loss rates in basins 1 and 2 remain the highest in the LCRB and Arizona.

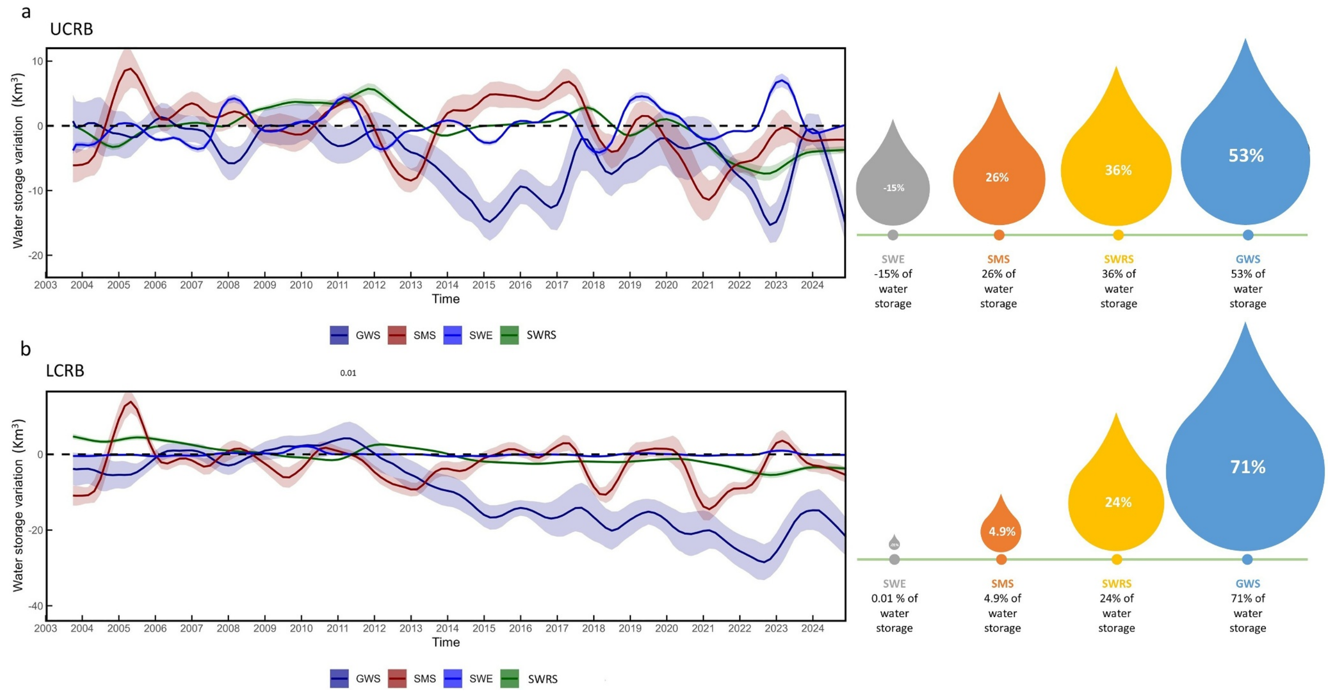

Figure 2. GRACE/FO TWS and contributing storage components. GRACE/FO-derived GWS changes along with SMS, SWE and SWRS changes (2003–2024). Trends given in Table 1. Units of monthly nonseasonal variations in water mass are in km^3, averaged over the (a) UCRB and (b) LCRB. The light shading represents uncertainty. The right panel reveals the contributions (%) of the different water storage components.

In contrast, basins 4–6, while also experiencing TWS loss, benefit from access to surface water, reducing their dependence on groundwater. These basins exhibit slower TWS loss rates, with rates of -6.8 ± 0.6, -6.8 ± 0.6, and -7 ± 0.9 mm/year, and corresponding GWS depletion rates of -5.4 ± 0.7, -5.8 ± 0.7, and -6.2 ± 1 mm/year (see Table S3 in Supporting Information S1). Notably, basin 4 includes Arizona's three largest AMAs—the Tucson, Pinal, and Phoenix AMAs—with groundwater use comprising approximately 50%, 50%, and 30% of the total water supply, respectively (ADWR, 2021b; Christiansen & Hamblin, 2023). This lower reliance on groundwater, alongside the management measures in place, appears to contribute to the slower rates of TWS and groundwater storage losses in these regions.

Agriculture accounts for more than 80% of total water use in Basin 1 and more than 60% in Basin 2 (WASSI-HUC8; Maupin et al., 2014), both of which are among the most rapidly depleting basins in Arizona. As noted above, the water supply in these basins is largely drawn from groundwater. Analysis in Text S4 of Supporting Information S1 revealed that the top 15 most water-intensive crops account for 71% and 55% of total crops in these two groundwater basins, respectively. Major crops contributing to water consumption in these regions, such as alfalfa and pecans, are also shown to emphasize the agricultural impacts on water consumption (Table S3 in Supporting Information S1). In basin 1, pecans account for 22% of the cropland, followed by double cropped Triticale/Corn (17%), alfalfa (15%), all of which are water-intensive crops. In basin 2, alfalfa dominates, accounting for 48% of the total crops grown. These crop percentages highlight the strong correlation between growing water-intensive crops and the declining groundwater availability in the LCRB.

4. Discussion

This and previous studies have clearly demonstrated that CRB groundwater is disappearing much faster than Colorado River streamflow and CRB surface water storage in Lakes Powell and Mead. However, CRB groundwater receives scant policy attention relative to surface water.

Consequently, groundwater depletion in the CRB has persisted since the 1980s, with the most pronounced losses concentrated in the LCRB (Castle et al., 2014; Scanlon et al., 2015). Recent threats to Colorado River water allocations are primarily driven by climate change, including reduced runoff and long-term aridification, along

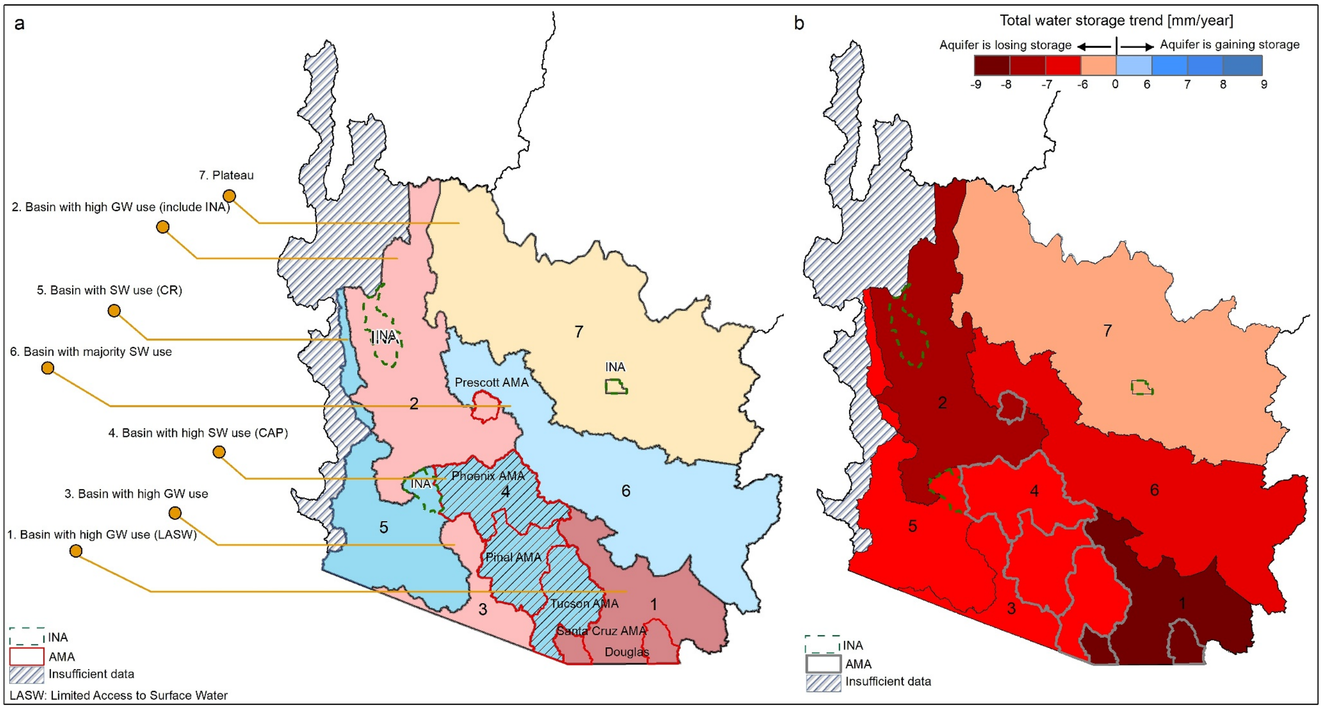

Figure 3. Categorization of groundwater basins based on water usage in the LCRB. (a) This classification map utilizes data from the University of Arizona and the Arizona Department of Water Resources (ADWR, 2016) to show the predominant source of water. Basins with significant access to surface water are shown in blue; (b) TWS trends (mm/year) from GRACE/FO for the groundwater basins in (a). The basins with the greatest loss rates are shown by progressively darker red colors.

with sustained over-reliance on declining reservoir storage, could cut surface water availability by 30% (Milly & Dunne, 2020; Stokstad, 2021; Udall & Overpeck, 2017; Whitney et al., 2023), forcing a shift to greater reliance on groundwater (Famiglietti, 2014; Liu et al., 2022). This scenario places the region's overall economy and agricultural productivity at significant risk, as an increase in reliance on groundwater is inevitable.

The efficacy of groundwater management policies in the LCRB is still under uncertain. In California, groundwater depletion is accelerating (Liu et al., 2022) despite ongoing implementation of the Sustainable Groundwater Management Act (https://water.ca.gov/programs/groundwater-management/sgma-groundwater-management). However, it is important to clarify that the most stringent SGMA curtailment measures have not yet taken full effect, and measurable improvements may take additional time to manifest.

As discussed above, Arizona's Groundwater Management Act has helped slow depletion rates in some AMAs. However, the majority of the AMAs are not on track to meet the sustainability goals set in 1980 to achieve safe-yield by 2025 (ADWR, 2016, 2020) (Figure 3b). Furthermore, groundwater simulations for the Phoenix AMA indicate complete depletion by the end of the century (ADWR, 2023). Notably, only 18% of Arizona (by area) is subject to groundwater management (Table S1 in Supporting Information S1), highlighting the urgent need for broader and more effective groundwater management across the entire LCRB.

Across the CRB, agriculture accounts for 52%–80% of water withdrawals, depending on whether total losses or direct human consumption are considered (Richter et al., 2020, 2024), 56% of which is used to produce feed for livestock (alfalfa and other grasses, hay, corn sileage, etc) (Richter et al., 2020). In the LCRB, and in particular, basins 1 and 2 in Figure 3, nearly all of these withdrawals come from groundwater, resulting in the rapid rates of depletion documented here. Efforts to reduce groundwater depletion in these regions would be strengthened by shifting away from water-intensive crops like cattle feed and perennial tree crops to more water-saving crops (Richter et al., 2023), and by shifting from inefficient flood irrigation to other, more efficient methods such as drip and deep-drip irrigation (Famiglietti, 2014).

Groundwater sustainability underpins human and environmental security in the LCRB. Yet climate change, limited groundwater management, and emerging pressures from the rapid growth of water and power intensive data centers and computer chip manufacturers in the region, pose major challenges to protecting groundwater for future generations.

There have been recent advances towards improving groundwater management in the LCRB and across the nation. Arizona is forming its seventh AMA around the Willcox basin near the state's southeastern corner, known for its extremely water intensive tree crops, vineyards, dairy farms, and cattle feed crops. At the national level, the U.S. President's Council of Advisors on Science and Technology (PCAST, 2023) recently released a national strategy for securing the country's groundwater resources. As discussed in the PCAST report, the GRACE/FO-based groundwater depletion rates presented here can serve as science-based targets that can help quantify the pumping reductions required to achieve regional sustainability.

As climate change intensifies and demands on the Colorado River continue to grow, the inclusion of groundwater in interstate CRB water discussions has become a national imperative. Historically managed at the state level, groundwater is now increasingly relied upon as surface water supplies dwindle, particularly in arid regions of the LCRB. However, the current patchwork approach to groundwater management in the U.S. has proven insufficient for long-term sustainability. In regions like Arizona and California, where reliance on groundwater is constantly increasing, federal oversight may be necessary to ensure that groundwater resources are effectively managed in conjunction with surface water allocations. This coordinated approach will be crucial to safeguard the future water security of the entire CRB.

Finally, it is critical that the U.S. intensively studies the risks of disappearing groundwater on its food production, its human and environmental health, climate resilience, and its long-term potential for economic growth. This is particularly true in the American Southwest, now more than ever, as its rapidly disappearing groundwater will come under increasingly severe stress.

Data Availability Statement

Publicly available data sets include GRACE and GRACE-FO (CSR, https://www2.csr.utexas.edu/grace/; GSFC, https://earth.gsfc.nasa.gov/geo/data/grace-mascons; JPL, https://search.earthdata.nasa.gov/search?q=GRACE%20JPL), Precipitation (CHIRPS version 2.0 data are available at: https://data.apps.fao.org/catalog/organization/chirps), global land surface models (SNODAS: https://nsidc.org/data/g02158/versions/1; NLDAS: https://disc.gsfc.nasa.gov/datasets?keywords=NLDAS). and In situ data includes groundwater level monitoring data from the Arizona Department of Water Resources (ADWR) Groundwater Site Inventory (GWSI; https://azwatermaps.azwater.gov/gwsiweb/) and reservoir storage (surface lakes): www.usbr.gov/UC/; or/LC. The archived data portals for these data sets are provided here, facilitating easy access for further research and analysis.

Acknowledgments

Funding was provided by Arizona Water Innovation Initiative (AWII) under an Interagency Service Agreement between the Arizona Governor's Office of Resiliency and Arizona State University (ASU). Additional funding was provided by ASU's Global Futures Laboratory. We thank ASU's Kyl Center for Water for open access to in situ groundwater observations in the CRB.

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