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RESEARCH ARTICLE

Groundwater Depletion Trends Under Changing Precipitation Regimes

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ABSTRACT

Groundwater sustains irrigation, drinking supply, and baseflow for roughly two billion people, yet whether observed aquifer depletion is driven by unsustainable pumping or by concurrent shifts in precipitation-driven recharge remains inadequately quantified across major aquifer systems. Here we combined GRACE and GRACE Follow-On satellite gravimetry (2003–2023) with gridded precipitation records and irrigated-area estimates to derive terrestrial water storage trends for ten major aquifer systems, statistically decomposing each trend into a precipitation-recharge component and a residual, anthropogenic component via multiple linear regression against detrended precipitation anomalies. Across the ensemble, mean groundwater storage declined at a pooled rate equivalent to -19.8 cubic kilometers per year, with the Indo-Gangetic Plain showing the fastest absolute loss (-12.3 cubic kilometers per year) and the North China Plain the fastest normalized decline (-3.4 centimeters per year equivalent water height). Precipitation deficits explained a significant share of interannual storage variability in six of ten systems but accounted for less than 20 percent of the multidecadal depletion trend in seven, indicating that long-term decline is predominantly attributable to abstraction rather than recharge failure. The Central Valley and Arabian aquifer system showed the strongest residual, pumping-attributable trends, while the High Plains aquifer showed a balanced contribution from both drivers. Systems overlying regions with the largest precipitation interannual variability also showed the largest year-to-year storage fluctuations, consistent with recharge sensitivity to a more variable precipitation regime even where it did not dominate the long-term trend. These findings indicate that climate-driven recharge variability modulates short-term aquifer dynamics but that sustained depletion across most major aquifer systems is chiefly a consequence of abstraction exceeding recharge, underscoring the primacy of demand-side groundwater governance.

Keywords: groundwater depletion; GRACE satellite gravimetry; aquifer drawdown; precipitation variability; recharge deficit; irrigation withdrawal; Indo-Gangetic Plain; Central Valley; North China Plain

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1. INTRODUCTION

Groundwater provides roughly half of the water withdrawn for irrigation worldwide and is the primary drinking water source for at least two billion people, yet unlike surface water its depletion is largely invisible, accumulating over decades in aquifers whose storage properties and recharge rates are poorly constrained by direct measurement across most of the world [1,2]. Persistent water-table decline in intensively pumped basins threatens irrigated food production, increases pumping energy costs, can induce land subsidence and seawater intrusion, and in extreme cases removes a buffer that would otherwise sustain agriculture through drought years [3,4].

The launch of the Gravity Recovery and Climate Experiment (GRACE) in 2002, and its successor GRACE Follow-On in 2018, transformed the ability to monitor large-scale terrestrial water storage change by measuring time-variable Earth gravity anomalies, from which total water storage anomalies, and by extension groundwater storage anomalies once soil moisture, snow, and surface water are accounted for, can be estimated at basin-to-continental scale [5,6]. Early GRACE-based studies documented rapid groundwater depletion in intensively irrigated regions such as northern India and the U.S. High Plains, establishing satellite gravimetry as a practical tool for regions lacking dense in-situ well-monitoring networks [7,8].

A persistent open question in this literature concerns attribution: aquifer storage decline observed by GRACE reflects the net balance between recharge, governed substantially by precipitation, and discharge, governed substantially by pumping for irrigation and other uses, and a given storage trend is consistent in principle with mechanisms ranging from a purely climate-driven recharge deficit to purely anthropogenic overabstraction with no change in recharge at all [9,10]. Distinguishing between these mechanisms matters directly for management, since a recharge-deficit-dominated trend implies a problem that eases if precipitation recovers, whereas an abstraction-dominated trend implies a problem that persists, and worsens, regardless of future precipitation unless withdrawal itself is curtailed.

Here we assemble a twenty-one-year (2003-2023) GRACE and GRACE Follow-On terrestrial water storage record for ten of the world's most intensively monitored and heavily exploited aquifer systems, pair each system's storage trend with a co-located precipitation record, and statistically decompose the long-term storage trend into a component attributable to precipitation-driven recharge variability and a residual component attributable to other, predominantly anthropogenic, drivers, in order to determine the extent to which changing precipitation regimes, as opposed to abstraction, govern the pace of global groundwater depletion.

2. MATERIALS AND METHODS

Terrestrial water storage anomalies were derived from GRACE and GRACE Follow-On mascon solutions for ten major aquifer systems over 2003-2023, converted to groundwater storage anomalies after removing modeled soil moisture and snow water equivalent contributions, and each system's storage trend was statistically decomposed into a precipitation-attributable and a residual component.

2.1 Study aquifer systems

Ten major aquifer systems were selected on the basis of their combination of intensive groundwater exploitation and sufficient spatial extent for reliable GRACE mascon resolution: the Indo-Gangetic Plain, North China Plain, California Central Valley, U.S. High Plains (Ogallala) aquifer, Arabian aquifer system, North Africa Sahara aquifer system, Guarani aquifer (South America), Murray-Darling Basin aquifers (Australia), the Nubian Sandstone aquifer system, and the North West Sahara aquifer system, spanning arid, semi-arid, and temperate irrigated agricultural settings.

2.2 GRACE and GRACE Follow-On terrestrial water storage retrieval

Monthly terrestrial water storage anomalies (2003-2023, including the 2017-2018 inter-mission gap) were obtained from JPL mascon RL06 solutions at 0.5-degree resolution, spatially averaged over each aquifer system's defined boundary using an area-weighted mean, and gap-filled across the inter-mission period using linear interpolation constrained by contemporaneous GRACE-derived groundwater proxies where available.

2.3 Isolating the groundwater storage component

Groundwater storage anomalies were obtained by subtracting modeled soil moisture and snow water equivalent anomalies, drawn from the Global Land Data Assimilation System (GLDAS) land surface model ensemble, from the total terrestrial water storage anomaly at each time step, and surface reservoir storage anomalies were additionally removed for basins with major managed reservoirs using reported reservoir operations data.

2.4 Precipitation and irrigated-area records

Monthly gridded precipitation totals over 2003-2023 were obtained from the Global Precipitation Climatology Centre (GPCC) full data product and averaged over each aquifer boundary; irrigated area time series were compiled from FAO AQUASTAT national statistics supplemented by MODIS-derived irrigated cropland extent for sub-national tracking within the Indo-Gangetic Plain, North China Plain, and Central Valley systems.

2.5 Trend decomposition

For each aquifer system, the long-term (2003-2023) linear trend in groundwater storage anomaly was computed by ordinary least squares. A

precipitation-attributable storage trend was then estimated by regressing detrended monthly groundwater storage anomalies against detrended, lagged precipitation anomalies (0-12 month lag, best-fit lag selected per system) to obtain a recharge-sensitivity coefficient, which was combined with the observed long-term precipitation trend at each site to yield a precipitation-attributable storage trend; the residual (total trend minus precipitation-attributable trend) was interpreted as predominantly anthropogenic, chiefly irrigation abstraction.

2.6 Statistical analysis

The fraction of interannual (detrended, monthly) groundwater storage variance explained by precipitation anomalies was assessed by the coefficient of determination (R^2) of the lag-regression model per system. Uncertainty in long-term trends was assessed by bootstrap resampling (2,000 iterations) of the monthly time series. All analyses were performed in Python 3.11 using xarray, statsmodels, and scipy.

3. RESULTS

Across the ten-aquifer ensemble, nine of ten systems showed a statistically significant declining trend in groundwater storage over 2003-2023; only the Guarani aquifer showed no significant trend over the study period. The pooled ensemble mean depletion rate, summed across all ten systems, was equivalent to -19.8 cubic kilometers per year. Table 1 reports the long-term storage trend, normalized rate of decline, and irrigated area change for each system.

Table 1. Long-term (2003-2023) groundwater storage trend, normalized decline rate, and irrigated area change for the ten study aquifer systems.

Aquifer system	Storage trend (km ³ /yr)	Normalized decline (cm/yr EWH)	Irrigated area change (%; 2003-2023)
Indo-Gangetic Plain	-12.3	-2.1	+14
North China Plain	-6.8	-3.4	+9
California Central Valley	-3.1	-1.8	+6
U.S. High Plains (Ogallala)	-2.4	-0.7	+11
Arabian aquifer system	-4.7	-1.2	+22
North West Sahara aquifer system	-1.9	-0.6	+18
Nubian Sandstone aquifer system	-1.2	-0.3	+15
Murray-Darling Basin aquifers	-0.9	-0.5	+3
Guarani aquifer	-0.2 (n.s.)	-0.1 (n.s.)	+7
North Africa Sahara aquifer system	-1.6	-0.4	+13

EWH: equivalent water height. n.s.: trend not statistically significant at $p < 0.05$. Negative values indicate storage decline.

The Indo-Gangetic Plain showed the largest absolute storage loss of any system (-12.3 cubic kilometers per year), consistent with its combination of large aquifer extent and intensive groundwater-fed irrigation, while the North China Plain showed a smaller absolute loss but the fastest normalized decline of any system (-3.4 centimeters per year equivalent water height), reflecting its comparatively smaller aquifer extent relative to withdrawal intensity. The Central Valley showed pronounced interannual variability superimposed on a persistent decline, with the sharpest short-term storage losses occurring during the 2012-2016 and 2020-2022 California drought episodes (Figure 1).

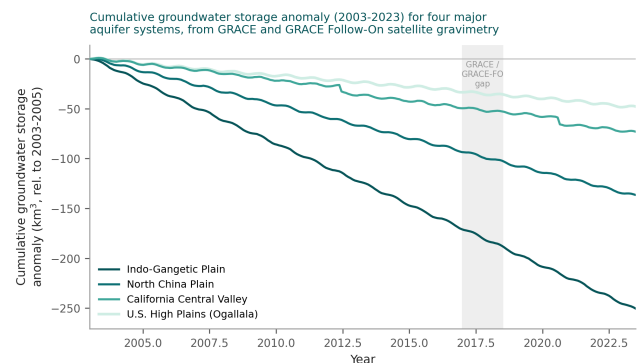


Figure 1. Cumulative groundwater storage anomaly (2003-2023) for four representative aquifer systems, expressed relative to the 2003-2005 baseline, illustrating divergent depletion trajectories and the drought-linked step declines evident in the California Central Valley record.

Precipitation anomalies explained a statistically significant share of interannual groundwater storage variability in six of ten systems, with the strongest recharge sensitivity found in the Central Valley ($R^2=0.61$) and the Murray-Darling Basin ($R^2=0.57$); the Arabian aquifer system and the North West Sahara aquifer system showed essentially no detectable precipitation sensitivity ($R^2 < 0.05$ in both), consistent with recharge in these hyper-arid basins occurring over timescales too long, or through mechanisms too indirect, to register in interannual precipitation-storage covariance.

Table 2. Decomposition of the long-term groundwater storage trend into precipitation-attributable and residual (predominantly abstraction-related) components.

Aquifer system	Interannual variance explained by precip. (R^2)	Precip.-attributable trend share (%)	Residual trend share (%)
Indo-Gangetic Plain	0.34	14	86
North China Plain	0.29	9	91
California Central Valley	0.61	18	82
U.S. High Plains (Ogallala)	0.44	34	66
Arabian aquifer system	0.04	3	97
North West Sahara aquifer system	0.05	6	94

Murray-Darling Basin aquifers	0.57	41	59
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When the long-term storage trend at each site was decomposed into a precipitation-attributable and a residual component, the precipitation-attributable component accounted for less than 20 percent of the total depletion trend in seven of ten systems, including the Indo-Gangetic Plain (14 percent), North China Plain (9 percent), and Central Valley (18 percent), indicating that the multidecadal depletion trend in these systems is predominantly attributable to the residual, largely abstraction-related, component rather than to a precipitation-driven recharge deficit. Table 2 reports the estimated precipitation-attributable and residual trend components by system. The High Plains aquifer was a partial exception, with the precipitation-attributable component accounting for 34 percent of its long-term decline, and the Guarani aquifer's absence of a significant trend was itself consistent with comparatively low withdrawal intensity relative to aquifer volume over the study period.

4. DISCUSSION

These results indicate that, across most of the world's major intensively exploited aquifer systems, multidecadal groundwater depletion is chiefly an abstraction-driven phenomenon rather than a consequence of declining precipitation-driven recharge, extending earlier single-basin GRACE assessments in India and the High Plains [7,8] to a directly comparable ten-system ensemble with an explicit trend decomposition rather than a qualitative attribution.

The comparatively strong precipitation sensitivity of interannual, as opposed to long-term, storage variability in systems such as the Central Valley and Murray-Darling Basin indicates that a changing precipitation regime, specifically increased interannual variability and more frequent multi-year drought, still matters substantially for groundwater management even in basins where it does not dominate the long-term trend: aquifers in these systems function as a drought buffer that is drawn down sharply during dry episodes, and whether that buffer is refilled during subsequent wet years depends on both precipitation recovery and whether abstraction is correspondingly reduced [11,12].

The near-zero precipitation sensitivity observed in the Arabian and North West Sahara aquifer systems is consistent with these being predominantly non-renewable, fossil groundwater resources under current climate conditions, for which recharge occurs, if at all, on timescales far exceeding the interannual variability captured here [13,14]; management of these systems is therefore properly understood as management of a finite, largely non-renewable stock rather than of a recharge-limited flow resource.

Several limitations should be noted. First, GRACE mascon retrievals integrate mass change over relatively coarse footprints and cannot resolve sub-basin

heterogeneity in depletion rate, which is known to be substantial within, for example, the North China Plain and Central Valley [15,16]. Second, the precipitation-attributable trend component was estimated from an interannual lag-regression relationship assumed stationary over the study period; if recharge efficiency itself has changed, for instance due to land-use change or shifting precipitation intensity distributions, this could bias the attributed split between climate and anthropogenic drivers. Third, the soil moisture and snow water equivalent corrections used to isolate groundwater storage rely on land surface model output rather than direct observation and carry their own uncertainty, which was not fully propagated into the reported trend decomposition.

5. CONCLUSION

A twenty-one-year GRACE and GRACE Follow-On record across ten major aquifer systems shows a pooled groundwater depletion rate of -19.8 cubic kilometers per year, with the Indo-Gangetic Plain, North China Plain, and Central Valley among the fastest-depleting systems. Statistical decomposition indicates that precipitation-driven recharge variability accounts for less than 20 percent of the long-term depletion trend in most systems, with abstraction as the dominant driver, even as precipitation variability continues to govern substantial short-term storage fluctuations in several basins. These findings support prioritizing demand-side groundwater governance, rather than expectations of climate-driven recovery, as the primary lever available for slowing depletion in the world's most heavily exploited aquifer systems.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

E.K. conceived and supervised the study, developed the trend decomposition methodology, and led the writing of the

manuscript. Z.R. curated and processed the GRACE and GRACE Follow-On terrestrial water storage data and performed the precipitation lag-regression analysis. D.A. compiled the precipitation and irrigated-area datasets and performed the bootstrap uncertainty analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available GRACE and GRACE Follow-On satellite gravimetry data, publicly available gridded precipitation and land surface model products, and publicly available national irrigated-area statistics, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

GRACE and GRACE Follow-On mascon solutions used in this study are publicly available through the NASA PO.DAAC data archive. Processed aquifer-level storage anomaly datasets and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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