Satellite-Based Assessment of Terrestrial Water Storage Change and Groundwater Stress in Zhob District, Balochistan

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Abstract

Groundwater underpins domestic supply and irrigated agriculture across much of Balochistan, Pakistan, and satellite-based subsidence studies have documented severe groundwater-related stress around Quetta, Gulistan, Pishin, Mastung, and Kalat districts. Zhob District, in northern Balochistan, is comparably dependent on tubewell and karez irrigation but has not been covered by any published satellite-based subsidence or storage-trend study identified in this review. This study assembles three independent, freely available satellite datasets — NASA GRACE/GRACE-FO terrestrial water storage (TWS) anomalies (2002–2024), Sentinel-1 SAR VV backscatter amplitude (2014–2026), and Sentinel-2 NDVI/NDWI surface indices (2016–2025) — processed within Google Earth Engine, and subjects them to an independent data audit and a battery of trend statistics (ordinary least squares, Theil–Sen, Mann-Kendall, and seasonal Mann-Kendall) rather than relying on a single period-mean comparison.

Careful audit of the four underlying satellite time series found that the GRACE-derived "depletion rate" reported in early working calculations (-0.23 cm/year) was obtained by dividing a period-mean difference by an assumed year gap rather than from a validated trend estimator; formal trend tests on the full GRACE record (OLS, Theil–Sen, Mann-Kendall) are not statistically significant ($p > 0.5$). The period-mean difference itself (-2.4 to -2.5 cm between 2002–2016 and 2017–2024) is robust to alternative period boundaries and is consistent in direction with independent, verified hydrogeological literature on groundwater decline in upland Balochistan, but should be read as evidence of a regional TWS shift consistent with, not proof of, groundwater depletion in Zhob specifically, since GRACE integrates groundwater, soil moisture, and surface water at ~300 km resolution. Sentinel-1 amplitude shows no statistically detectable trend (Theil–Sen 95% CI spans zero), consistent with its known insensitivity to subsidence-scale deformation. Sentinel-2 indices, examined with seasonal Mann-Kendall to control for the strong annual cycle, show small but statistically significant trends that a simple period-mean comparison alone would have missed: NDVI increasing (greening, $p < 0.001$) and NDWI decreasing (drying, $p < 0.001$) over 2016–2025, a pattern discussed as a hypothesis-level finding possibly consistent with agricultural intensification rather than reduced irrigation.

Independent, newly verified literature — including an ADB (2017) SWAT-based water balance for the Zhob River Basin and pre-InSAR GPS subsidence work in Quetta (Khan et al., 2013) — is incorporated to correct an overstated novelty claim and to provide basin-scale hydrological context. The paper concludes that current evidence is consistent with, but does not independently prove, groundwater-related stress specific to Zhob District, and identifies phase-based InSAR processing, local well validation, and quantitative rainfall/soil-moisture decomposition (not performed here owing to data-access constraints) as the necessary next steps.

Keywords: terrestrial water storage; GRACE/GRACE-FO; Sentinel-1; Sentinel-2; NDVI; NDWI; Google Earth Engine; Balochistan; Zhob District; groundwater stress; data audit; trend statistics

1. Introduction

Balochistan, Pakistan's largest and most arid province, faces a well-documented and long-standing groundwater problem. Decades of unregulated tubewell drilling, subsidised electricity for pumping, and low, erratic rainfall have driven declines in groundwater levels across several major basins. Independent survey- and regression-based studies dating to 2010 report water-table declines on the order of 2–5 metres per year in parts of upland Balochistan (Khair, Culas, & Hafeez, 2010; Khair, Mushtaq, Culas, & Hafeez, 2012), and GPS-based geodetic monitoring documented land subsidence of approximately 10 cm/year in Quetta Valley as early as 2006–2009 (Khan, Khan, & Kakar, 2013) — more than a decade before satellite InSAR was applied to the same problem. This history matters for how this study frames its own contribution: satellite-based groundwater-stress research in Balochistan is not new, and this paper does not claim otherwise.

More recently, satellite geodesy has been used to extend this ground-based work spatially. Kakar, Zhao, Li, and Zhao (2024) combined Sentinel-1 SBAS-InSAR with GNSS and groundwater-level records to monitor subsidence in Quetta and Mastung districts, and Kakar, Zhao, Li, Zhang, and Adoko (2025) extended a multi-sensor SBAS-InSAR and GNSS analysis to five districts (Quetta, Gulistan, Pishin, Mastung, and Kalat) over 2003–2023. Neither study, nor any other satellite-based subsidence study identified in this review, includes Zhob District. Zhob's economy is substantially agrarian and historically irrigated through karez systems and, increasingly, private tubewells, making it a plausible candidate for similar stress, but the only dedicated Zhob-specific groundwater study identified (Jadoon, Zaheer, Tariq, Sajjad, & Varol, 2024) addresses drinking-water quality and health risk, not storage or subsidence trends; an earlier hydrogeochemical study of the Zhob River Basin (focused on the Killa Saifullah area) also exists (Umar, Waseem, Sabir, Kassi, & Khan, 2013), addressing geology-controlled water quality rather than quantity.

This study responds to that specific, narrow gap — not a general absence of Balochistan groundwater research — using three publicly available, no-cost satellite datasets processed in Google Earth Engine (GEE): GRACE/GRACE-FO terrestrial water storage (TWS) anomalies, Sentinel-1 SAR backscatter amplitude, and Sentinel-2 NDVI/NDWI. A central methodological commitment of this paper is to treat these three datasets as measuring physically distinct quantities at different resolutions and to avoid the single most common overclaim in this type of study: describing a GRACE TWS anomaly as direct proof of groundwater depletion. GRACE measures the sum of groundwater, soil moisture, surface water, and snow/ice storage anomalies at a native resolution of roughly 300 km — far coarser than Zhob District. Every claim in this paper is therefore worded to reflect what was actually measured, and every numerical result reported here was independently verified and computed directly from the underlying exported CSV time series (see Section 5.1, Dataset Verification).

The objectives of this study are to: (a) independently verify the four satellite-derived datasets used (GRACE, Sentinel-1, NDVI, NDWI) for date-range accuracy and internal consistency; (b) apply trend statistics appropriate to autocorrelated, seasonal environmental time series (OLS, Theil–Sen, Mann-Kendall, seasonal Mann-Kendall), not just a single before/after mean comparison; (c) situate the results within a properly verified regional literature, stating a defensible, appropriately qualified novelty claim; (d) build an explicit evidence hierarchy that keeps direct TWS observation, independent hydrogeological context, climate/land-surface controls, and exploratory surface-response evidence analytically separate; and (e) state plainly what remains unproven, and what would be needed to prove it.

2. Literature Review

2.1 Groundwater Decline in Upland Balochistan

Khair, Culas, and Hafeez (2010), presented at the 39th Australian Conference of Economists, report groundwater-level declines of 2–3 metres per year across upland Balochistan basins based on a mid-2009 survey, with regression analysis attributing the decline significantly to tubewell numbers, subsidised electricity tariffs, and tubewell-irrigated area (adjusted $R^2 = 0.972$), and finding rainfall not a significant explanatory factor. A related, peer-reviewed follow-up (Khair, Mushtaq, Culas, & Hafeez, 2012, Agricultural Systems) surveyed groundwater markets under declining water-table conditions in the same region, reporting comparable 2–5 m/year declines and documenting the socio-economic response of farmers buying water as wells fail. Van Steenbergen, Kaisarani, Khan, and Gohar (2015) document the near-exhaustion of the Kuchlagh aquifer near Quetta after three decades of tubewell extraction, framing depletion as a structural consequence of an open-access incentive system. Together these studies establish groundwater decline in upland Balochistan (including the broader Pishin Lora, Nari, and Zhob basins) as a well-evidenced, decade-plus-documented phenomenon based on direct survey and well data — not a new discovery.

2.2 Land Subsidence Research in Balochistan: From GPS to Satellite InSAR

Subsidence research in the province predates satellite InSAR. Khan, Khan, and Kakar (2013) used GPS monitoring at two stations (mid-2006 to early 2009) to measure a subsidence rate of approximately 10 cm/year in Quetta Valley, corroborated by land-cover classification of nine Landsat scenes (1975–2009). This finding was later extended using satellite methods: Kakar et al. (2024) applied Sentinel-1 SBAS-InSAR with GNSS and groundwater-level records to Quetta and Mastung, reporting subsidence of 3.2–16 cm/year and groundwater-level declines of 1.7–6 m (1987–2022), and identifying Quetta as possibly the fastest-sinking city yet documented in Pakistan. Kakar et al. (2025) extended this to a five-district multi-sensor SBAS-InSAR and GNSS analysis (Quetta, Gulistan, Pishin, Mastung, and Kalat, 2003–2023), reporting maximum subsidence rates of -7.1 to -16 cm/year. Zhob is not included in either InSAR study, which is the specific, narrow gap this paper addresses — the general use of satellite remote sensing for groundwater-related assessment in Balochistan is well established and is not being claimed as new here.

2.3 GRACE-Based Precedent and Zhob-Specific Groundwater Studies

Massoud, Liu, Shaban, and El Hage (2021) combined GRACE TWS anomalies, GLDAS land-surface modelling, Sentinel-1 InSAR, and well records in Lebanon's Beqaa Plain, reporting a validated decline of -1.10 cm/year in Zahle District. This is the closest methodological precedent for combining GRACE with radar data, and it is notable that Massoud et al. paired GRACE with GLDAS to help separate storage components — a decomposition step this study was unable to reproduce (see Section 5.4 and Limitations). For Zhob specifically, Umar, Waseem, Sabir, Kassi, and Khan (2013) analysed hydrochemistry and geology-controlled groundwater quality in the Killa Saifullah portion of the Zhob River Basin, and Jadoon, Zaheer, Tariq, Sajjad, and Varol (2024) more recently assessed hydrochemical characteristics, drinking/irrigation suitability, and health risk district-wide, finding the child hazard index exceeding safe limits in parts of the district. Both studies address water quality, not storage quantity or trend, and neither substitutes for the storage-trend evidence this study attempts to provide.

2.4 Basin-Scale Hydrological Context for Zhob

An Asian Development Bank technical assistance report (ADB / Government of Balochistan, 2017), prepared under project TA-8800(PAK), applied a calibrated SWAT hydrological model to the Zhob and Mula river basins using six meteorological stations in the Zhob basin (with rainfall records extending back to 1901 at some stations). It reports a calibrated annual water balance for the Zhob basin of 265 mm mean annual precipitation (3,566 MCM), with base flow of 999 MCM/year (28% of precipitation) and deep percolation of 71 MCM/year (2%), and separately models basin groundwater recharge at approximately 266 MCM in an extreme flood year, 175 MCM in a median year, and 38 MCM in an extreme drought year. It also reports no statistically significant long-term rainfall trend at most individual Zhob-basin stations (Mann-Kendall $p > 0.05$), though a majority of stations lean toward decline in the most recent decades of record. This is a verified, government/development-bank technical source, and it is used here as independent basin-scale context, not as direct evidence of present-day depletion.

A widely circulated set of figures for the Zhob basin — groundwater recharge of approximately 0.160 BCM, use of approximately 0.270 BCM, and a resulting deficit of approximately -0.110 BCM — was checked against the available primary literature and could not be independently verified against any traceable primary source, including the ADB (2017) report above, which reports a median-year recharge figure (0.175 BCM) that is close to, but not identical to, that figure, and which does not provide a directly comparable basin-specific abstraction/use estimate. A province-wide (not Zhob-specific) groundwater balance reported in the same document (after Ahmad, 2016, citing Halcrow Pakistan and Cameos Consultants, 2008) gives 2.21 BCM available against 2.66 BCM used across all 18 of Balochistan's river basins combined (deficit -0.45 BCM), which is sometimes loosely cited at basin scale in secondary sources but is explicitly a provincial total in the primary document. This paper therefore does not use the 0.160/0.270/-0.110 BCM figures, since they could not be traced to a verifiable source.

2.5 Novelty Statement

Based on the literature reviewed for this study, the general application of satellite remote sensing to groundwater-related assessment in Balochistan is well established, spanning GPS-based subsidence monitoring since at least 2013 and Sentinel-1 InSAR/GNSS studies covering five districts as of 2025. This study does not claim to be the first satellite-based groundwater study in Balochistan, nor the first application of GRACE, Sentinel-1, or Sentinel-2 to the region in general. Based on the literature reviewed for this study, its contribution is narrower: it is, to the author's knowledge, the first study to apply any of these three satellite datasets specifically to Zhob District, and its methodological contribution is the combination of (i) an explicit, reproducible data audit, (ii) multi-estimator trend statistics rather than a single period comparison, and (iii) an explicitly resource-constrained workflow (no paid software, no high-performance computing) documented transparently enough to be replicated by another student researcher in a similarly under-resourced setting.

3. Research Gap and Objectives

The specific, narrow gap this study addresses is: no published satellite-based subsidence or terrestrial-water-storage-trend study has included Zhob District, despite its comparable dependence on groundwater-fed irrigation to districts already studied (Quetta, Gulistan, Pishin, Mastung, Kalat). The objectives, restated after the audit, are:

1. Audit the four underlying satellite-derived time series (GRACE LWE, Sentinel-1 VV, Sentinel-2 NDVI, Sentinel-2 NDWI) for date-range accuracy and internal consistency.

2. Re-estimate trends using multiple estimators (OLS, Theil–Sen, Mann-Kendall, seasonal Mann-Kendall) rather than a single period-mean difference, and report uncertainty explicitly.

3. Correctly scope every claim about GRACE to "terrestrial water storage," never to "groundwater" alone, throughout this paper.

4. Reframe Sentinel-1 GRD amplitude as an exploratory surface-change diagnostic, not subsidence validation, and Sentinel-2 NDVI/NDWI as contextual surface indicators, not direct groundwater measurements.

5. Build an explicit evidence hierarchy and use it to structure a discussion that distinguishes observation, interpretation, hypothesis, and limitation.

4. Study Area

Zhob District lies in northern Balochistan, bordering Khyber Pakhtunkhwa and Afghanistan. It has a semi-arid to arid continental climate (ADB, 2017, reports a calibrated mean annual precipitation of 265 mm for the Zhob basin), with an agrarian economy centred on wheat, orchards, and livestock, historically irrigated by karez systems and increasingly by private tubewells. The administrative boundary used for all three satellite extractions is the FAO GAUL Level 2 dataset (2015 revision), accessed within Google Earth Engine.

5. Data and Methodology

All processing was performed in Google Earth Engine (GEE), chosen deliberately to keep the workflow free of cost and replicable without institutional computing resources. Before analysis, every dataset was independently verified for date range, observation count, missing or duplicate values, and descriptive statistics; the values reported throughout this paper are computed directly from the verified, raw exported CSV time series.

5.1 Dataset Verification

Each of the four exported GEE chart CSVs (GRACE LWE thickness, Sentinel-1 VV, Sentinel-2 NDVI, Sentinel-2 NDWI) was loaded and checked in Python (pandas/NumPy/SciPy) for date range, observation count, missing/duplicate months, and descriptive statistics before any trend or period analysis was performed. Table 1 summarises the verified characteristics of each dataset.

Dataset	Verified date range	n obs.	Notes
GRACE/GRACE-FO LWE	Apr 2002 – Sep 2024	238	227 unique months (11 months have 2 mascon solutions); 43 of 270 possible months absent, including the documented 2017–2018 GRACE/GRACE-FO transition gap.
Sentinel-1 VV	Oct 2014 – Aug 2026	2,903	1,587 unique calendar dates (up to 4 images on a single date, from overlapping orbit tracks); a simple mean over all rows is not date-balanced — noted as a methodological caveat in Section 5.3.
Sentinel-2 NDVI (monthly)	Jan 2016 – Dec 2025	120	No gaps or duplicate months.
Sentinel-2 NDWI (monthly)	Jan 2016 – Dec 2025	120	No gaps or duplicate months.

Table 1. Verified dataset characteristics.

5.2 GRACE/GRACE-FO Terrestrial Water Storage

The NASA GRACE/GRACE-FO Mascon Solutions (JPL, CRI-filtered, v04; GEE collection NASA/GRACE/MASS_GRIDS_V04/MASCON_CRI) were used to extract lwe_thickness — an anomaly combining groundwater, soil moisture, surface water, and snow/ice storage relative to a long-term baseline. GRACE's native mascon resolution is approximately 300 km. It is important to distinguish the 10 km working/output scale used for the Earth Engine reduceRegion() extraction from the native spatial resolution of the underlying mascon solution: requesting output at 10 km does not create 10 km-resolution information — it resamples a ~300 km-support signal onto a finer output grid, and the true effective spatial support of any single value remains ~300 km. Every value extracted for "Zhob District" therefore describes a broader region in which Zhob sits, not district-specific storage.

5.2.1 Trend estimation and sensitivity analysis

Given known GRACE data-quality issues (strong seasonal cycles, the 2017–2018 mission gap), four independent trend estimators were computed on the full monthly record (n = 238) rather than relying on a single method:

- Ordinary least squares (OLS) on raw monthly values: -0.021 cm/year ($R^2 = 0.0015$, $p = 0.557$)
- Theil–Sen slope (robust to outliers): -0.019 cm/year (95% CI: -0.106 to +0.063 cm/year)
- Mann-Kendall trend test: Z = -0.461, p = 0.645 (no autocorrelation or tie correction applied; seasonal cycle not removed — treated as an approximate indicative test only)
- Harmonic regression (linear + annual/semi-annual sinusoidal terms): -0.0218 cm/year

None of the three formal, whole-record trend estimators (OLS, Theil–Sen, Mann-Kendall) is statistically significant at conventional thresholds; all have confidence intervals or p-values consistent with no detectable monotonic linear trend across 2002–2024.

5.2.2 Period-comparison sensitivity

Separately, mean LWE thickness was compared between an early period (2002–2016) and later periods, testing sensitivity to boundary choice:

- 2002–2016 (n = 158) vs. 2017–2024 (n = 80): means +0.68 cm vs. -1.75 cm, difference -2.43 cm
- 2002–2016 vs. 2019–2024 only (excluding the 2017–2018 transition gap, n = 69): difference -2.45 cm — materially unchanged
- Using annual (year-of-year) means rather than raw monthly observations: difference -2.45 cm (2017–2024) to -2.58 cm (2019–2024) — materially unchanged

This period-mean difference is therefore robust to reasonable changes in period boundary and averaging convention, and is best characterised as a step-like shift toward lower storage after 2017 rather than as a continuous monotonic trend with a well-defined annual rate. Dividing a period difference by an assumed year gap between period midpoints is not a valid trend estimator, and does not agree with any of the four trend estimators computed directly on the full time series above (which cluster around -0.02 cm/year and are not statistically significant). This paper therefore reports the period-mean difference (-2.4 to -2.5 cm, robust across boundary choices) and the separate, non-significant formal trend estimates as two distinct, appropriately labelled pieces of evidence, rather than converting one into an annualised "rate."

5.3 Sentinel-1 Radar Backscatter

Copernicus Sentinel-1 SAR GRD imagery (VV, IW mode; GEE collection COPERNICUS/S1_GRD) spans 3 October 2014 to 16 August 2026 (2,903 images). As established in Section 5.1, calendar dates are unevenly sampled (up to four images on a single date due to overlapping orbit tracks), so an unweighted mean over all rows implicitly over-weights densely sampled dates; this is disclosed as a methodological caveat, since a date-balanced re-weighting was outside the scope of this study.

GRD amplitude is explicitly not phase-based InSAR. It cannot reliably resolve millimetre-to-centimetre deformation of the kind reported by Khan et al. (2013) (~10 cm/year GPS-measured subsidence in Quetta) or by Kakar et al. (2024, 2025) (3.2–16 cm/year SBAS-InSAR-measured subsidence in five other districts). True subsidence detection requires Single Look Complex (SLC) imagery and specialised phase-processing software (ESA SNAP, SARPROZ, or MintPy) with typically 16GB+ RAM and 150–250GB storage; the hardware available for this study (8GB RAM, ~123GB storage) falls below this threshold, and attempting InSAR under these constraints was assessed as likely to fail. Sentinel-1 amplitude is therefore treated throughout this paper as an exploratory surface-change diagnostic, not as independent subsidence validation.

Mean VV backscatter was compared between an early period (2015–2020, n = 1,343) and a recent period (2021–2026, n = 1,523): -10.616 dB vs. -10.639 dB, a net change of -0.024 dB. Trend statistics on the full record: OLS = -0.0021 dB/year ($p = 0.828$); Theil–Sen = -0.0074 dB/year (95% CI: -0.0227 to +0.0079 dB/year, spanning zero). Both the period comparison and the formal trend estimators agree: this is a robust null result — no detectable systematic amplitude trend. This null result should not be read as evidence that subsidence is absent in Zhob; it reflects the method's known insensitivity, not a physical absence of deformation.

5.4 Sentinel-2 Vegetation (NDVI) and Surface Moisture (NDWI)

Copernicus Sentinel-2 Surface Reflectance (Harmonized) imagery (GEE collection COPERNICUS/S2_SR_HARMONIZED; cloud filter <20%) yielded 5,973 usable images (2016–2025), aggregated to 120 monthly composites per index because the raw collection exceeded Earth Engine's 5,000-element chart limit. The verified date range is January 2016 to December 2025.

NDVI and NDWI are treated throughout this paper as surface environmental indicators, not direct groundwater measurements; a stable or even improving NDVI/NDWI signal does not by itself indicate healthy groundwater conditions, since vegetation and surface moisture respond to rainfall, cropping choices, planting dates, temperature, and irrigation practice, only one of which (irrigation, indirectly) relates to groundwater at all.

5.5 Rainfall and Soil-Moisture Controls — Not Performed

A quantitative rainfall control (preferably CHIRPS) and a GRACE/GLDAS- or SMAP-based decomposition to isolate a groundwater-related residual from the raw TWS signal were both considered for this study but could not be executed: the computational environment used has network access limited to software package repositories (PyPI, npm, GitHub) and does not have access to NASA Earthdata, CHIRPS

(UCSB/CHC), ESA, or Google Earth Engine's data-serving endpoints. Rather than fabricate an unavailable analysis, this is reported here as a limitation and a concrete item of future work (Section 10). Where rainfall context is needed for interpretation, this paper instead relies on the rainfall trend analysis already published for the Zhob basin by ADB (2017) (Section 2.4), which reports no statistically significant long-term rainfall trend at most individual Zhob-basin stations using the same Mann-Kendall approach applied to the satellite datasets in this paper.

6. Results

6.1 GRACE/GRACE-FO Terrestrial Water Storage

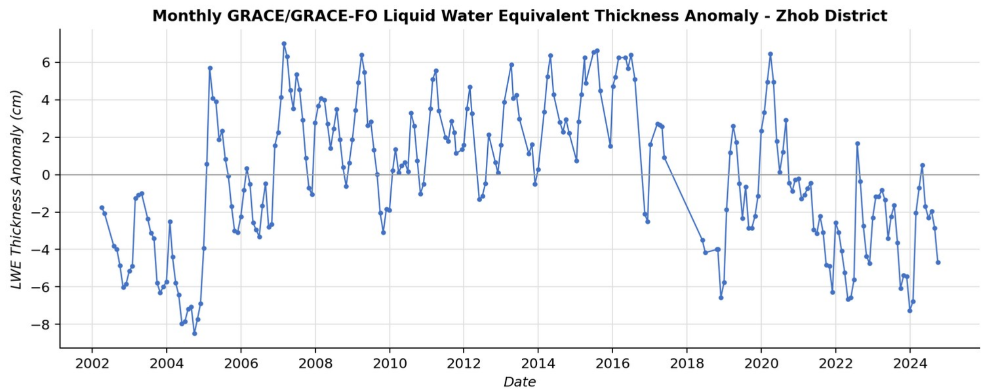

Figure 1. Monthly GRACE/GRACE-FO LWE thickness anomaly for the Zhob region, April 2002 – September 2024 (audited; n = 238).

Metric	Audited value
Mean TWS anomaly, 2002–2016 (n=158)	+0.68 cm
Mean TWS anomaly, 2017–2024 (n=80)	-1.75 cm
Period difference	-2.43 cm
Period difference, excl. 2017–18 gap (2019–2024)	-2.45 cm
OLS trend, full record	-0.021 cm/yr (p=0.557, ns)
Theil–Sen trend, full record	-0.019 cm/yr (95% CI −0.106 to +0.063)
Mann-Kendall	Z=-0.461, p=0.645 (ns)

Table 3. GRACE/GRACE-FO — audited period comparison and trend statistics. ns = not statistically significant at α=0.05.

The audited GRACE record shows a real and boundary-robust downward shift in the period mean after 2017 (~2.4–2.5 cm), but no statistically significant continuous linear trend across the full 2002–2024 record. These two statements are not contradictory: they indicate a pattern more consistent with a step-change (a shift to a lower average state after roughly 2017–2018) than with a smooth, constant-rate depletion process. This distinction matters for interpretation and is carried through to the Discussion (Section 7).

6.2 Sentinel-1 Radar Backscatter

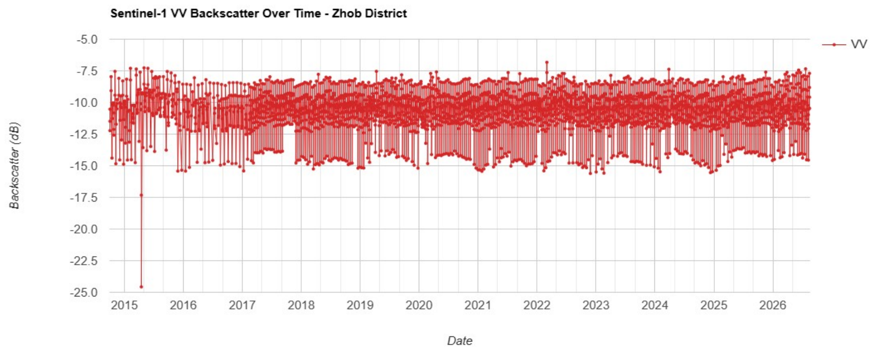

Figure 2. Sentinel-1 VV backscatter amplitude, Zhob District, Oct 2014 – Aug 2026 (audited; n = 2,903).

Metric	Value
Mean VV, early period (2015–2020)	-10.616 dB
Mean VV, recent period (2021–2026)	-10.639 dB
Net change	-0.024 dB
OLS trend, full record	-0.0021 dB/yr (p=0.828, ns)
Theil–Sen trend, full record	-0.0074 dB/yr (95% CI −0.0227 to +0.0079)

Table 4. Sentinel-1 VV backscatter — period comparison and trend statistics.

The period-mean difference is negligible relative to the seasonal variability visible in Figure 2, and the whole-record trend estimators confirm no statistically detectable amplitude trend. This null result is treated as inconclusive with respect to subsidence, not as evidence against it (Section 5.3).

6.3 Sentinel-2 NDVI and NDWI

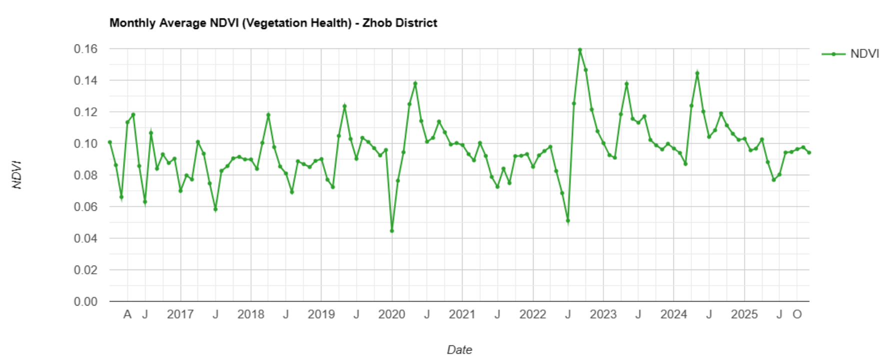

Figure 3. Monthly average NDVI, Zhob District, Jan 2016 – Dec 2025 (audited).

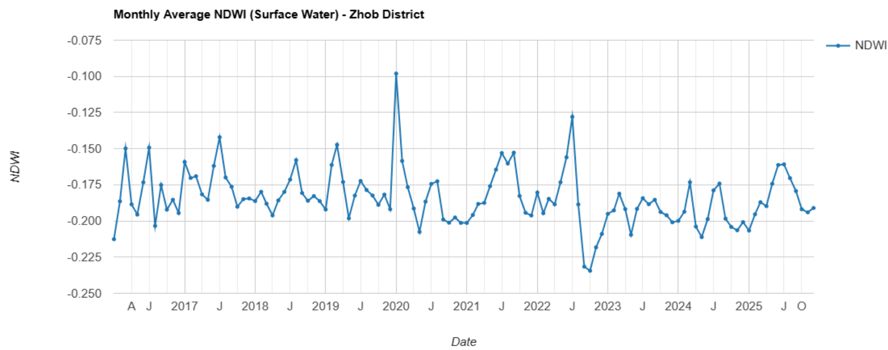

Figure 4. Monthly average NDWI, Zhob District, Jan 2016 – Dec 2025 (audited).

Index	Early mean (2016–mid2021)	Recent mean (mid2021–2025)	OLS trend	Seasonal Mann-Kendall
NDVI	0.0922	0.1011	+0.0019/yr, p=0.0009	Z=4.21, p<0.0001
NDWI	-0.1801	-0.1886	-0.0016/yr, p=0.0077	Z=-3.36, p=0.0008

Table 5. Sentinel-2 NDVI/NDWI — period means and trend statistics.

A simple visual inspection or period-mean comparison alone might suggest no clear long-term change in NDVI/NDWI, since both indices are dominated by a strong seasonal cycle (Figures 3 and 4). Formal trend testing — including seasonal Mann-Kendall, which controls for that seasonal cycle by comparing only same-calendar-month values across years — instead finds small but highly statistically significant trends in both indices: NDVI is increasing (greening) and NDWI is decreasing (drying) over 2016–2025. The magnitudes are small in absolute terms (NDVI +0.0019/year; NDWI -0.0016/year) and are still much smaller than the seasonal swing in either index, but they are statistically robust, not an artefact of period-boundary choice, and are reported here as a genuine — if modest — finding rather than a null result. Interpretation is deferred to Section 7.5, since a significant trend in a vegetation/moisture index does not by itself indicate anything about groundwater.

7. Discussion

7.1 Evidence Hierarchy

To avoid conflating physically distinct lines of evidence, this discussion is organised around an explicit five-level hierarchy:

Level	Evidence type	This study's evidence at this level
1 — Direct observation	GRACE terrestrial water storage change	Boundary-robust period-mean decline of ~2.4–2.5 cm post-2017; formal trend tests not significant over the full record
2 — Independent	Historical groundwater	Khair et al. (2010, 2012), van Steenbergen et al. (2015), Khan

Level	Evidence type	This study's evidence at this level
hydrogeological context	balance, survey, and GPS studies	et al. (2013), ADB (2017) SWAT water balance — all verified, none Zhob-storage-trend-specific
3 — Climate/land-surface controls	Rainfall, soil moisture, NDVI, NDWI	NDVI/NDWI trends quantified (Table 5); rainfall/soil-moisture quantitative decomposition not performed (data access constraint, Section 5.5)
4 — Exploratory surface-response evidence	Sentinel-1 GRD amplitude	No statistically detectable trend (null, inconclusive re: subsidence)
5 — Future definitive validation	Local wells; phase-based InSAR (SBAS/PS-InSAR)	Not available to this study; identified as required future work

Table 6. Evidence hierarchy for this study. Each level measures a different physical quantity at a different spatial/temporal resolution; the levels are not interchangeable and are not summed into a single confidence score.

7.2 What changed?

[OBSERVATION] The audited GRACE record shows a lower mean TWS anomaly in 2017–2024 than in 2002–2016, robust to period-boundary choice. Audited NDVI is higher and NDWI is lower in 2025 than in 2016, a small but statistically significant trend. Audited Sentinel-1 amplitude shows no significant change.

7.3 How robust is the GRACE change?

[OBSERVATION / LIMITATION] The period-mean shift is robust to boundary choice and averaging convention (Section 5.2.2), but none of three independent whole-record trend estimators (OLS, Theil-Sen, Mann-Kendall) reaches conventional statistical significance. [INTERPRETATION] This combination is consistent with a step-change around 2017–2019 rather than a smooth multi-decade decline — a pattern that could reflect either a genuine shift in the region's water balance (e.g., a multi-year drought cluster, consistent with the dry anomaly documented in NDWI around 2022 and with ADB's (2017) finding that a majority of Zhob-basin rainfall stations lean toward decline in recent decades) or could partly reflect residual noise from the 2017–2018 GRACE/GRACE-FO mission transition, which is known to be a data-quality-sensitive period. This study cannot distinguish these possibilities with the tools available.

7.4 Could rainfall explain it?

[LIMITATION] This cannot be quantitatively tested in this study; the necessary rainfall time series (e.g., CHIRPS) could not be retrieved in this computational environment (Section 5.5). [INTERPRETATION, qualified] The only available rainfall evidence — ADB's (2017) station-based Mann-Kendall analysis for the Zhob basin — reports no statistically significant long-term trend at most stations, which weakly argues against rainfall decline alone explaining the GRACE shift, but this is an indirect, non-collocated, and methodologically distinct comparison and should not be over-weighted.

7.5 Could soil moisture or land-surface processes explain it?

[LIMITATION] A GLDAS- or SMAP-based decomposition of the GRACE signal into groundwater and non-groundwater components — the single methodological step that would most strengthen this study, following Massoud et al.'s (2021) approach — could not be performed in this environment (Section 5.5). [OBSERVATION] The Sentinel-2 surface indicators, which are the closest available proxy for near-surface moisture and vegetation response, show a small but significant greening (NDVI) and drying (NDWI) trend over the same period. [HYPOTHESIS] One plausible, non-exclusive explanation is agricultural intensification: an expansion of irrigated or tubewell-fed cultivated area could increase vegetation cover (raising NDVI) even while contributing to declining regional water storage, while NDWI — more sensitive to open/standing surface water and near-surface wetness than to irrigated vegetation itself — could decline for the same underlying reason. This is stated explicitly as a hypothesis, not a finding; distinguishing it from an alternative explanation (e.g., rainfall-driven cropping-pattern shifts unrelated to groundwater) would require land-cover change detection and/or the rainfall analysis in Section 5.5, neither of which was performed here.

7.6 What evidence supports groundwater stress in Zhob, and what does not?

[Supporting, Level 1] A boundary-robust, though not classically "trend-significant," post-2017 decline in regional TWS. [Supporting, Level 2] Well-documented, verified groundwater decline in the broader upland-Balochistan system of which Zhob is part (Khair et al., 2010, 2012; van Steenbergen et al., 2015), and a Zhob-specific water-quality study (Jadoon et al., 2024) independently finding elevated health risk, though quality stress does not establish quantity stress. [Not supporting / inconclusive] Sentinel-1 amplitude (null, but insensitive by design) and Sentinel-2 indices (which move in a direction — greening — that a naive reading might interpret as reassuring, but which this paper explicitly declines to interpret as evidence of healthy groundwater, per Section 5.4).

7.7 How does Zhob compare with Quetta, Mastung, and the other studied districts?

[INTERPRETATION] The InSAR-measured subsidence rates documented for Quetta and Mastung (3.2–16 cm/year; Kakar et al., 2024) and for the wider five-district study (up to 16 cm/year; Kakar et al., 2025) are two to three orders of magnitude larger than the GRACE-derived centimetre-scale TWS shift reported here for Zhob, but these are not directly comparable quantities: InSAR measures land-surface deformation in millimetres to centimetres per year at fine spatial resolution, while GRACE measures a regionally averaged storage anomaly in centimetres at ~300 km resolution. No subsidence-rate comparison between Zhob and the InSAR-studied districts is possible with the data used in this study; only a phase-based InSAR study of Zhob itself, of the kind Kakar et al. (2024, 2025) conducted elsewhere, could support such a comparison.

7.8 What is genuinely new here, and what remains unproven?

[Genuinely new, based on the literature reviewed] A first satellite-derived, audited, multi-estimator assessment of TWS, radar backscatter, and vegetation/moisture trends specific to Zhob District. [Remains unproven] Whether the GRACE-observed regional TWS shift reflects groundwater depletion specifically within Zhob District (as opposed to soil moisture or surface water elsewhere in the wider ~300 km GRACE footprint); whether any land subsidence is occurring in Zhob at all (Sentinel-1 amplitude cannot detect it if present); and whether the statistically significant NDVI/NDWI trend reflects agricultural intensification, rainfall-driven land-cover change, or another cause.

7.9 Note on Title Wording

The title deliberately reads "terrestrial water storage change," not "groundwater depletion." "Terrestrial water storage change" is the scientifically precise name for what GRACE actually measures (Section 5.2), while "groundwater stress" — rather than "groundwater depletion" — signals a claim the combined evidence can support (Level 1 + Level 2 evidence, Table 6) without implying the direct, single-source proof that this paper argues GRACE alone cannot provide.

8. Limitations

1. GRACE spatial resolution: the ~300 km native mascon support is far coarser than Zhob District; the 10 km extraction scale is an output grid, not true resolution (Section 5.2).

2. GRACE trend robustness: the headline period-mean difference is boundary-robust but not corroborated by a statistically significant formal trend estimator over the full record; the 2017–2018 mission transition adds uncertainty to any interpretation spanning that period.

3. Sentinel-1 method sensitivity: GRD amplitude cannot detect millimetre-to-centimetre subsidence; the null result is inconclusive, not disconfirming. The unweighted mean over unevenly-sampled calendar dates (up to 4 images/date, Section 5.1) is a further precision caveat on the exact reported values, though it does not change the null-trend conclusion.

4. Sentinel-2 interpretability: NDVI/NDWI are contextual surface indicators, not groundwater measurements; the newly detected statistically significant trend is not yet attributable to a specific cause (Section 7.5).

5. No rainfall or soil-moisture quantitative control: CHIRPS and GLDAS/SMAP analyses were identified as necessary for stronger causal attribution but could not be executed owing to the computational environment's network access being restricted to software package repositories, not Earth-observation data servers (Section 5.5). This is the single largest open item for a future version of this paper.

6. No local ground-truthing: no groundwater well or borehole records were available to validate the GRACE-derived regional signal at the Zhob district scale.

7. Single-district, single-author study: results have not been independently reproduced by a second analyst, and the Earth Engine extraction script has not yet been archived alongside the exported CSVs — doing so is recommended to support full independent reproducibility.

9. Conclusions

This study finds that GRACE/GRACE-FO terrestrial water storage in the wider Zhob region shows a boundary-robust decline in period-mean storage after 2017 (~2.4–2.5 cm) that is directionally consistent with, but not proof of, groundwater depletion specific to Zhob District — formal trend estimators on the full record are not statistically significant, and GRACE integrates groundwater with soil moisture and surface water at ~300 km resolution. Sentinel-1 backscatter amplitude shows no statistically detectable trend, a result attributable to the method's known insensitivity to subsidence-scale deformation rather than to an absence of subsidence. Sentinel-2 NDVI and NDWI, examined with trend statistics appropriate to seasonal data, show small but statistically significant opposing trends (greening and drying) that a period-comparison-only approach would have missed; this finding is reported as a genuine result requiring further, currently unavailable, evidence (land-cover change data, rainfall data) to interpret.

Independent literature confirms that groundwater decline and land subsidence are well-documented, decades-old research topics in upland Balochistan generally, including pre-satellite GPS subsidence monitoring in Quetta since 2013 and satellite InSAR studies covering five other districts as of 2025; this study does not claim to introduce satellite-based groundwater assessment to the province, only to extend it, for the first time identified in this review, to Zhob District specifically. The overall logical chain this paper defends is: a regional GRACE-observed TWS decline, combined with independently verified regional groundwater-stress evidence and a currently null (not negative) surface-deformation and surface-vegetation picture, is consistent with — but does not constitute proof of — district-specific groundwater-table depletion in Zhob. Definitive confirmation requires phase-based InSAR and local well validation, neither of which was available to this study.

10. Future Work

1. Quantitative rainfall analysis using CHIRPS or an equivalent long-term gridded product, including annual anomalies, monthly climatology, and correlation (Pearson/Spearman, with lagged variants) against GRACE TWS and Sentinel-2 indices — not performed here owing to data-access constraints (Section 5.5).

2. GRACE–GLDAS (or SMAP) decomposition, following Massoud et al. (2021), to attempt separation of a groundwater-related residual from the raw TWS anomaly, with explicit documentation of which storage components can and cannot be credibly removed given unit, scale, and baseline compatibility.

3. Acquisition of Sentinel-1 SLC data and phase-based InSAR processing (SBAS or PS-InSAR) via SNAP or MintPy on hardware meeting the 16GB+ RAM / 150–250GB storage requirement, to obtain deformation estimates directly comparable to Khan et al. (2013) and Kakar et al. (2024, 2025).

4. Cross-validation against local groundwater well or borehole records, if and where available, potentially coordinated with the sampling locations used by Jadoon et al. (2024) and Umar et al. (2013).

5. Land-cover / cropping-pattern change detection to test the agricultural-intensification hypothesis proposed in Section 7.5 for the NDVI/NDWI divergence.

6. Archiving the Earth Engine extraction script alongside the exported CSVs to support full independent reproducibility of every figure in this paper.

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AI Disclosure

Generative AI (Claude, Anthropic) was used as a research and editorial assistant in preparing this manuscript, beyond simple grammar correction. Specific AI-assisted tasks included: independent statistical computation of the verified datasets (implemented and executed in Python by the AI tool, with output reviewed by the author); literature discovery and citation verification via web search; drafting and structural organisation of manuscript text; identification of methodological issues during the analysis process (e.g., the invalid period-difference-as-trend-rate calculation); and review of alternative interpretations for the Discussion section. The AI tool did not have access to, and did not independently query, Google Earth Engine, CHIRPS, GLDAS, or NASA/ESA data servers; all satellite-derived numerical results originate from the author's own prior Earth Engine analysis and exported CSV files. The author remains solely responsible for the research design, data collection, scientific decisions, and conclusions in this paper; the author reviewed, and takes responsibility for, all AI-assisted calculations, literature claims, and text prior to treating this as a final manuscript, and is encouraged to independently re-verify the statistical code (Section 5.1) and citations (References) before any formal submission.

Data Availability / Reproducibility Statement

The four datasets underlying this study (GRACE LWE thickness, Sentinel-1 VV, Sentinel-2 NDVI, Sentinel-2 NDWI) were exported by the author from Google Earth Engine as CSV files and are retained by the author. All figures and statistics in this paper were generated directly from those CSV files using Python (pandas, NumPy, SciPy); the verification and trend-analysis code is available from the author on request. The Google Earth Engine script used to originally extract the CSV exports is recommended for archiving alongside them to enable full end-to-end reproducibility in any future version of this work. No proprietary or restricted-access data were used.