Tracking groundwater depletion and droughts in Saudi Arabia with GRACE data

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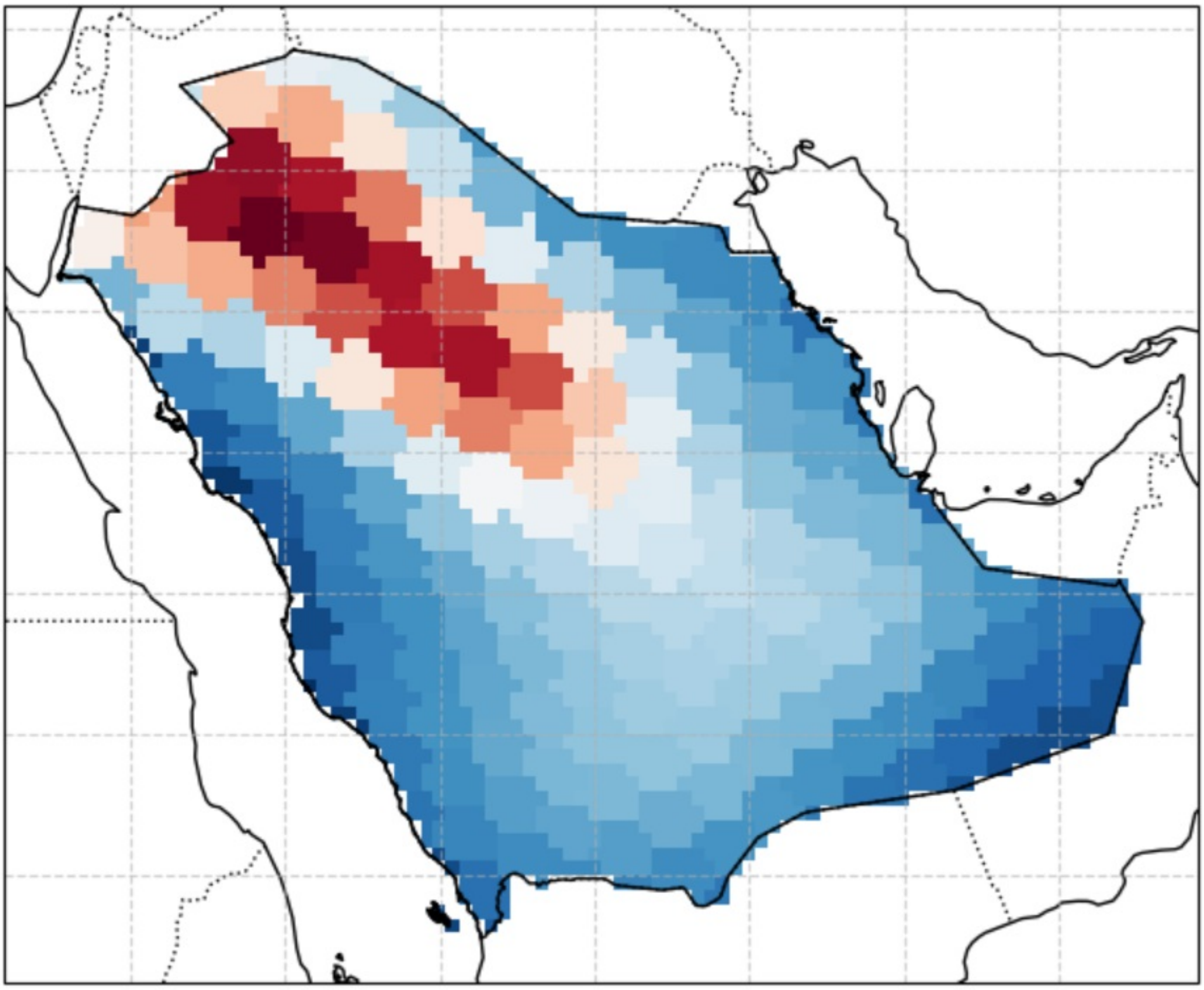

1 Introduction

Understanding changes in ground water storage is a critical aspect of resource management for countries, companies and organizations across the world. This is particularly true for arid areas, where rare rainfall means groundwater management has an out-sized impacts on agriculture, industry, human consumption and the environment. The Gravity Recovery and Climate Experiment (GRACE) and its successor, GRACE Follow-on (GRACE FO), have enabled the study of large scale hydrological processes, by providing monthly measurements of total water storage anomalies. GRACE data alone cannot distinguish types and sources of water on its own - it must therefore be complemented by other datasets to provide understanding of local hydrological processes such as rainfall, surface water storage, or moisture storage.

This project aims to answer the question of "How GRACE can track droughts and groundwater use in Saudi Arabia". Indeed, despite popular belief, Saudi Arabia experiences seasonality and water cycles. Yet, heavy demand from various human activities in the region has resulted in heavy aquifer pumping, leading to measurable groundwater depletion. This phenomenon can be tracked by combining GRACE data with PCR-GLOBWB and GLEAM datasets to yield estimations in groundwater storage anomalies.

Using various datasets, we were able to localize the aquifers most used by the country to meet its demand, and clearly plot the seasonal variability of both the ground water storage and the soil moisture.

2 Data and Methodology

2.1 Water Balance Framework

The core of this analysis relies on decomposing terrestrial water storage (TWS) anomalies observed by GRACE into its major hydrological components, in order to isolate and quantify changes in groundwater storage over Saudi Arabia. GRACE and GRACE-FO provide total vertically integrated water column anomalies, but do not distinguish between surface, soil, snow, and groundwater contributions. In arid environments like Saudi Arabia—where snow and rain are minimal (less than 150mm of rainfall per year on average [1])—the key components influencing TWS are soil moisture (SMS), surface water storage (SWS), and groundwater storage (GWS). It is relevant to note that soil moisture and surface water storage account in large part for whatever rainfall does exist in any given year.

We adopt the following mass balance equation:

$$\Delta\text{TWS} = \Delta\text{SMS} + \Delta\text{SWS} + \Delta\text{GWS}$$

This can be rearranged to isolate groundwater anomalies:

$$\Delta\text{GWS} = \Delta\text{TWS} - \Delta\text{SMS} - \Delta\text{SWS}$$

This approach assumes that snow water equivalent (SWE) and canopy interception are negligible within the study area, as Saudi Arabia does not retain any snow cover, and has virtually no tree cover ([1], [3]). Each component of the equation is derived from an independent, state-of-the-art dataset described below.

2.2 GRACE Data

Total water storage anomalies were obtained from the GRACE and GRACE-FO missions, using mascons JPL RL06M (3° resolution solution) and CSR mascons (1° resolution solution), covering the period from 2002 to 2024. The data provides monthly anomalies relative to a baseline mean period (2004–2009), gridded at a spatial resolution of 3°.

The GRACE data were pre-processed to remove global glacial isostatic adjustment (GIA) effects and converted to liquid water equivalent (LWE) in millimeters. In our stage of the data analysis, the LWE anomaly was converted to volumes (cubic kilometers), in order to standardize the comparison with other datasets. No additional filtering or destriping was applied due to the use of mascon data, which are already regularized. All datasets were regridded and masked to align with the spatial extent of Saudi Arabia, excluding its ocean territory.

2.3 GLEAM Data

Soil moisture anomalies were derived from the Global Land Evaporation Amsterdam Model (GLEAM v3.6a), which provides daily global estimates of surface and root-zone soil moisture based on satellite observations and a Priestley–Taylor-based evapotranspiration model. We used monthly averaged data at 0.25° spatial resolution and integrated across all soil layers to produce total root-zone soil moisture storage in millimeters.

Data were aggregated to match the temporal and spatial resolution of the GRACE anomalies. Anomalies were computed relative to the same baseline period as GRACE to ensure consistency in the ΔSMS term. It must be noted that, in the context of this analysis, only surface moisture was considered, for three primary reasons. Primarily, Saudi Arabia exhibits low rainfall combined with rapid evaporation or pooling (into reservoirs or rivers). Additionally, the data for root-level moisture exhibited high levels of noise, rendering the global trend difficult to read. Finally, it was considered that deep soil moisture is closely related to ground-water storage, thus rendering a distinction less relevant in the context of this study.

2.4 PCR-GLOBWB Data

Surface water storage anomalies were estimated using PCR-GLOBWB (version 2), a global hydrology and water balance model developed at Utrecht University. PCR-GLOBWB simulates terrestrial hydrological processes including river storage, lake levels, wetlands, and small reservoirs, and provides monthly output at a native resolution of 5 arcminutes ($\sim$10 km).

We extracted model outputs for the study region and aggregated them to monthly averages over Saudi Arabia. The ΔSWS component was calculated by summing all relevant surface water compartments simulated by the model. As with other components, the anomalies were computed relative to a consistent baseline. However, the available dataset was restrained with an end date of 2016, limiting the period of interest in this study, as all datasets were required to match in timelines.

Finally, each dataset provides one of the variables of our equation. It yields:

$$\Delta \text{GWS} = \Delta \text{TWS}_{\text{GRACE}} - \Delta \text{SMS}_{\text{GLEAM}} - \Delta \text{SWS}_{\text{PCR-GLOBWB}}$$

2.5 CEIC Oil Extraction Volume

Finally, it was suggested that the results of the study could be biased by the high volumes of oil extracted from Saudi Arabia. Data comprising the monthly oil extraction volumes was obtained from the CEIC, and converted to the same volume units (km^3) and time-resolution (monthly) as other datasets.

2.6 Principal Component Analysis (PCA) on GRACE Data

To further explore the dominant spatial and temporal modes of terrestrial water storage change, we applied Principal Component Analysis (PCA) to GRACE-derived total water storage anomalies (ΔTWS). The initial analysis was conducted using the JPL RL06M mascon solution at 3°

resolution. However, the spatial resolution proved insufficient for isolating region-specific patterns, and the results were sensitive to grid boundaries. PCA was particularly valuable for isolating the dominant depletion signal across Saudi Arabia without requiring prior assumptions about the spatial structure of water loss.

We therefore repeated the analysis using the CSR RL06 mascon product, which offers 1° spatial resolution and improved performance in arid regions with localized water changes. The GRACE CSR mascons were first masked to the extent of Saudi Arabia and stacked into a matrix of spatial grid cells over time. PCA was then used to extract orthogonal spatial patterns (Empirical Orthogonal Functions, EOFs) and their corresponding time series (Principal Component scores).

The first and second principal component (PC1, PC2) were retained for interpretation, as they accounted for the majority of the variance in ΔTWS across the region. The first component provides a data-driven perspective on the most significant hydrological signal over Saudi Arabia, which was then compared with our earlier results derived from the water balance equation, while the second one shows seasonality of water storage, to be analyzed alongside soil and moisture storage (with seasonality).

3 Results

3.1 Total Water Storage Anomalies (GRACE)

The GRACE-derived total water storage anomaly (ΔTWS) over Saudi Arabia shows a clear, sustained downward trend from 2003 through 2024 (Figure 1). The cumulative loss over this period exceeds 20 km^3, with the steepest declines occurring between 2007 and 2016. This strongly suggests persistent water loss across the region, likely dominated by unsustainable extraction. Minor interannual variability is observed, but the dominant feature is a linear decline, consistent with groundwater depletion.

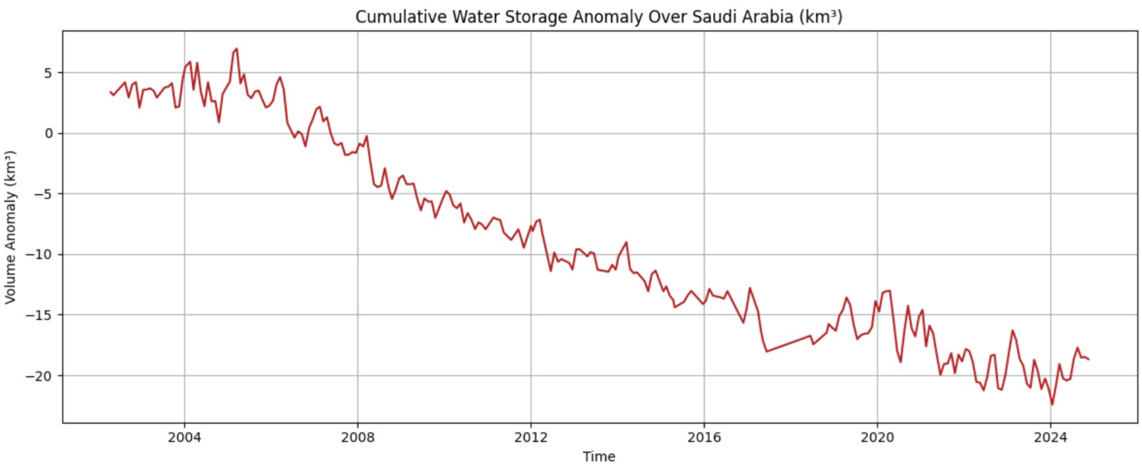

Figure 1: Cumulative Water Storage Anomaly over Saudi Arabia, in cubic kilometers 2002-2025.

3.2 Surface Water Storage (PCR-GLOBWB)

Surface water storage anomalies (ΔSWS), derived from PCR-GLOBWB, reveal a relatively flat pattern, with short-term fluctuations but no sustained trend. Seasonal variations are present, and a few peaks are observed (notably around 2005 and 2009), but the average remains close to the 2004–2009 baseline. This confirms that surface water bodies do not significantly contribute to the long-term decline seen in GRACE TWS.

This seasonability of the data can also be observed in the second component of the principal component analysis of the mascons dataset (Figure 3). Indeed, we can observe that a minimum is reached during each summer every year, while a maximum is obtained at the middle of winter, towards each year's end. Finally, this PCA analysis can also help determine which year is more subjected to drought, by comparing the value of the different minimum for various years.

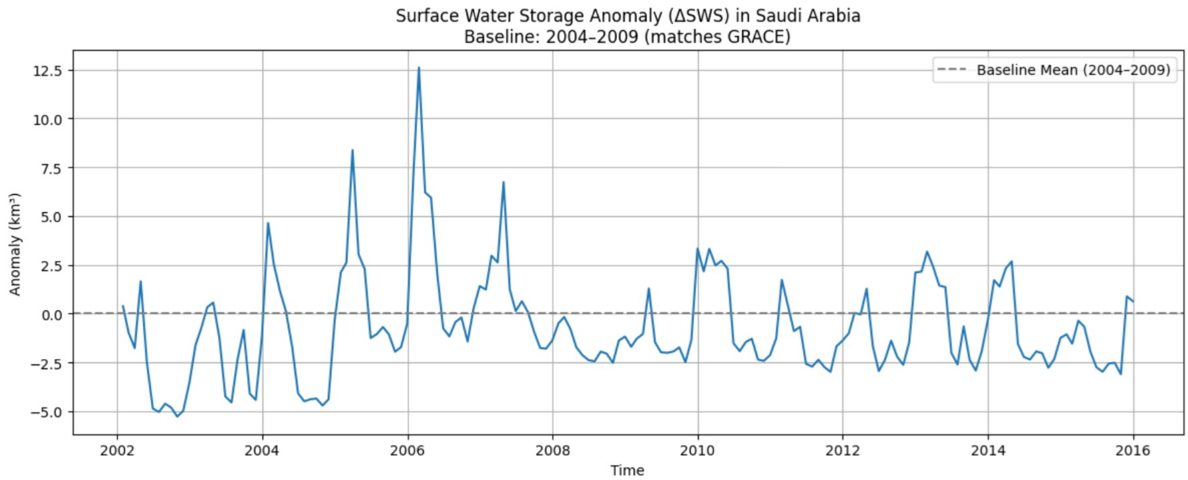

Figure 2: Surface Water Anomaly with GRACE baseline.

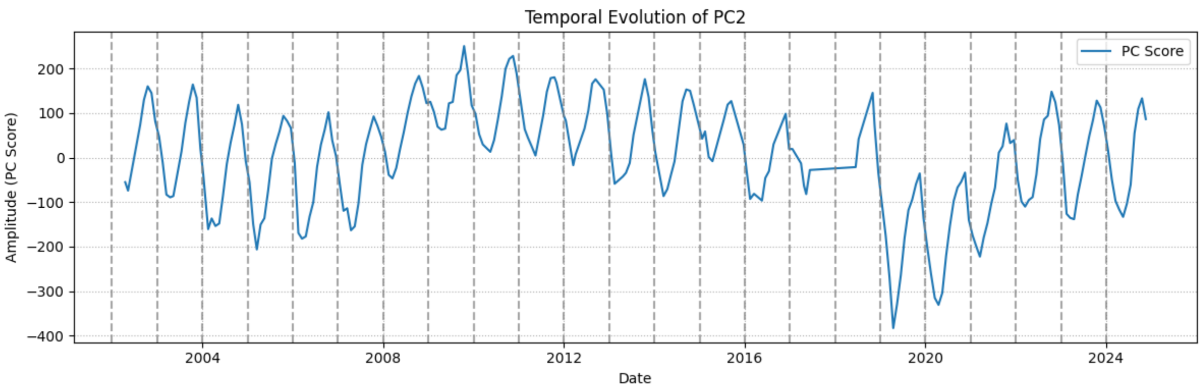

Figure 3: Temporal evolution of component 2 of the PCA

3.3 Soil Moisture Storage (GLEAM)

Soil moisture anomalies (ΔSMS), computed from GLEAM's surface layer only, show strong seasonal oscillations but no meaningful long-term trend during the overlapping period (2002–2016). Peaks and troughs align with known seasonal precipitation events, and anomalies consistently revert toward the baseline mean. This indicates that soil moisture is highly variable but does not explain the persistent water storage loss observed in GRACE.

3.4 Groundwater Storage

By subtracting surface water storage (PCR-GLOBWB) and soil moisture storage (GLEAM) from total water storage (GRACE), we isolate the groundwater storage anomaly (ΔGWS) over Saudi Arabia (Figure 2). The result reveals a striking and persistent downward trend between 2002 and 2016.

Over the 14-year period, groundwater storage decreased by more than 15 km^3, with a linear trend of approximately -1.61 km^3/year. Seasonal variability is superimposed on this trend, but the signal is dominated by steady depletion.

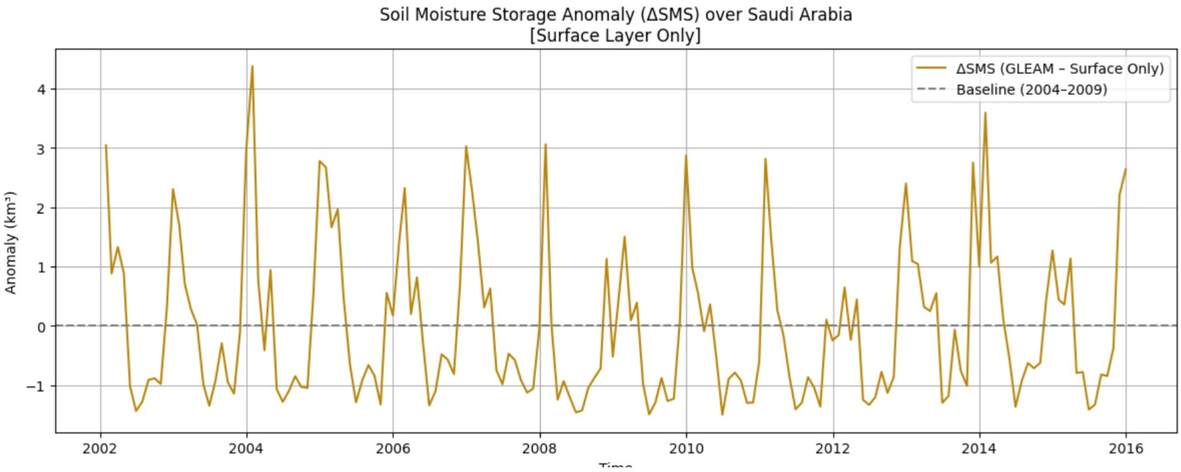

Figure 4: Soil Moisture Anomaly with GRACE Baseline.

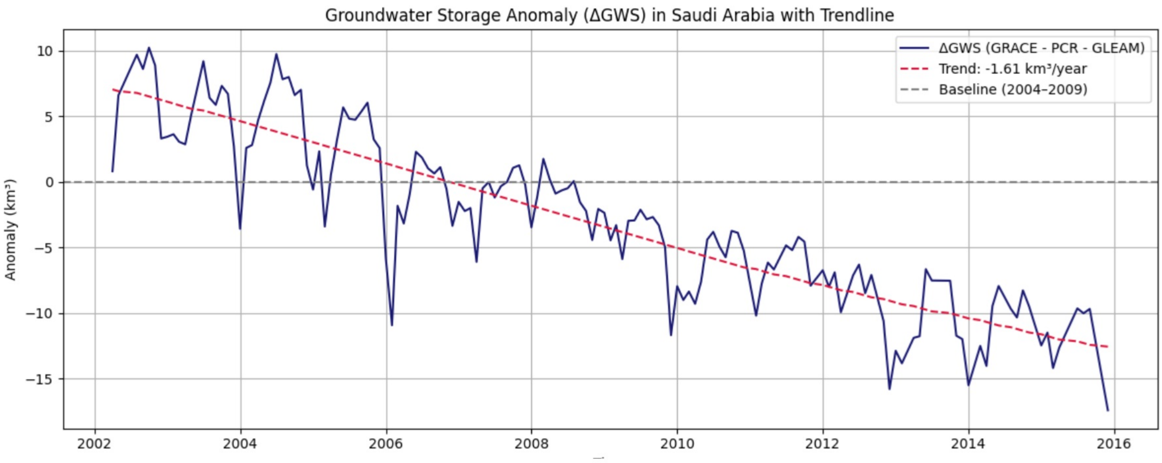

Figure 5: Final Groundwater Storage Anomaly from 2002-2016.

This rate of decline is consistent with the widespread use of non-renewable groundwater for agriculture and urban supply in Saudi Arabia. Unlike surface and soil moisture storage, which exhibit no significant long-term trend, the ΔGWS series points to groundwater extraction as the principal driver of regional water loss.

The magnitude of groundwater depletion is substantial when compared to national water consumption statistics. In contrast, estimated water loss due to oil extraction over the same period is orders of magnitude smaller, suggesting that it has no discernible impact on GRACE-detectable water mass change. This comparison underscores the dominance of groundwater pumping as the critical factor affecting terrestrial water storage in the region.

3.5 Oil Extraction

It was also considered that oil extraction may represent a significant share of what the analysis detected as groundwater depletion. As a heuristic process, the investigation was extended to include the entirety of Saudi Arabia's oil and gas extraction volumes - in a first step, not excluding ocean-based extraction. The volumes were converted to the same units as other datasets, in cubic kilometers.

It must be noted that the volume of fossil fuel depletion is many orders of magnitude smaller than groundwater use. Thus, with no further analysis, it was concluded that oil extraction was not a relevant factor in the observed trends. This is confirmed by further subtracting extracted oil volumes from the groundwater storage anomaly, which yields a perfect 1:1 mapping (at the

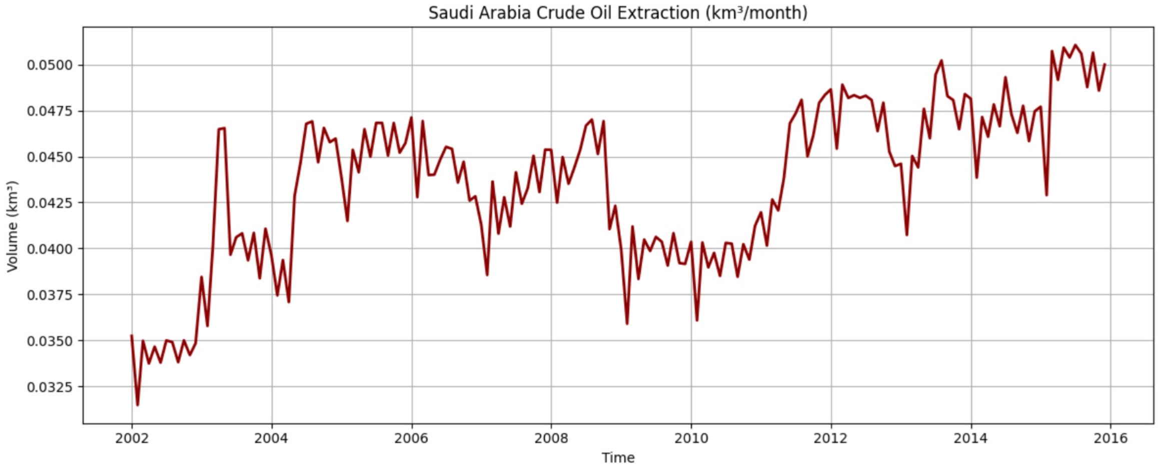

Figure 6: Saudi Arabia fuel extraction in cubic kilometers.

relevant magnitudes).

3.6 Principal Component Analysis Results

The PC1 time series shows a sustained downward trend from 2002 to 2023, with minor seasonal fluctuations superimposed on a long-term signal. This indicates a persistent and progressive water mass loss over time. The red curve, a 12-month moving average, highlights the smooth decline in water storage corresponding to the spatial pattern of PC1.

The associated spatial loading pattern of PC1 reveals a dominant zone of mass loss centered in northwestern Saudi Arabia, a region known for intensive groundwater extraction. Areas in the southern and eastern regions exhibit negative loadings, suggesting either lesser correlation or opposing-phase behavior. This spatial decomposition aligns well with known agricultural and hydrological pressures concentrated in the northwest: the area highlighting higher spatial correlation with described water loss corresponds to known aquifers in Saudi Arabia, the large "Saq" aquifer. Conversely, lower correlation in the South and east can be explained by the presence of more human activity - i.e. more industry, basins, and water use. Overall, these two figures explain the human impact of shifting water resources from aquifers (such as the Saq aquifer) to populated and agricultural areas.

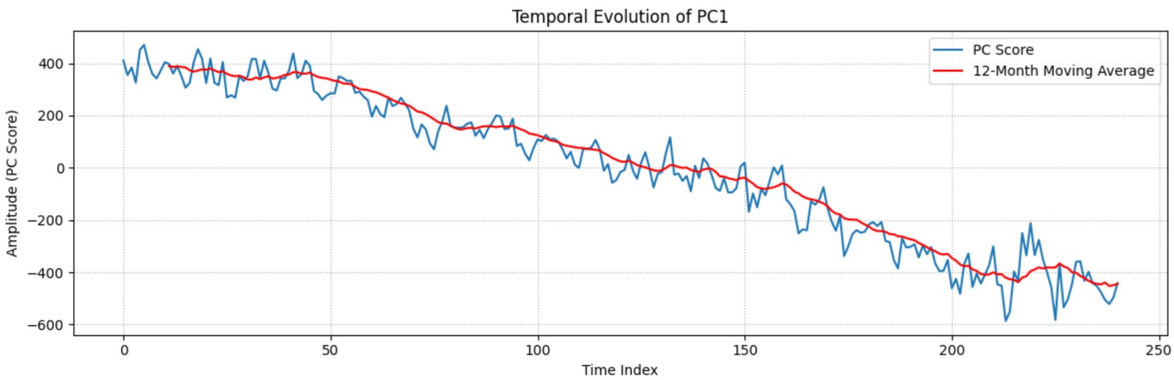

Figure 7: First mode of PCA Analysis using CSR Mascons.

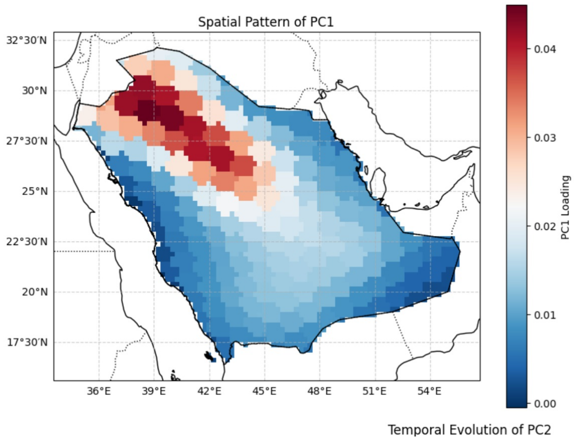

Figure 8: *
(a) PC1 spatial loading using CSR Mascons

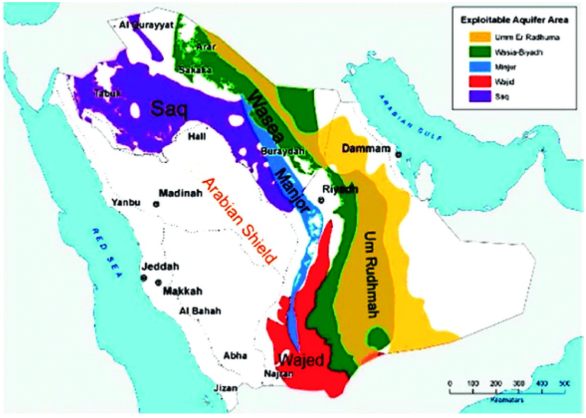

Figure 9: *
(b) Map of Saudi Arabian aquifers, [2]

Figure 10: Comparison between PC1 spatial pattern from PCA and the known aquifer locations in Saudi Arabia. The northwestern region shows strong correlation with areas of known groundwater use.

4 Discussion

The results of this study confirm that Saudi Arabia is experiencing a substantial and sustained decline in groundwater storage, with losses averaging approximately -1.61 km^3/year between 2002 and 2016. This trend is consistent with earlier satellite-based assessments and reflects the heavy reliance on non-renewable fossil groundwater to support agricultural expansion, urban development, and industrial use in one of the world's most water-scarce regions.

The decomposition of total water storage into individual hydrological components allowed us to attribute the observed losses with confidence. Both soil moisture and surface water exhibited short-term variability but no persistent downward trend, reinforcing the conclusion that groundwater is the dominant source of water loss detected by GRACE. This approach strengthens the case for satellite gravimetry as a critical tool for monitoring invisible subsurface depletion where in situ data are sparse or unavailable.

Our findings also address a common misconception: that oil extraction might meaningfully affect GRACE-based mass change. Back-of-the-envelope calculations suggest that total subsurface volume extracted as oil or gas is negligible in comparison to groundwater withdrawals, both in mass and volume. Given that a cubic kilometer of groundwater ($\sim$ 1 trillion liters) weighs approximately 1 gigatonne, even modest annual changes are detectable via GRACE. We found no evidence that oil extraction plays any detectable role in GRACE-observed mass loss across Saudi Arabia, though different methodologies may provide tailored results for such topic of interests.

However, this study has a few limitations. First, the assumption that snow water and canopy interception are negligible is valid for this region but may not generalize elsewhere. Second, while the PCR-GLOBWB and GLEAM datasets are state-of-the-art, they come with model-based and remote sensing uncertainties, respectively. Temporal and spatial harmonization across products may also introduce minor inconsistencies. Lastly, we used the surface layer of GLEAM for soil moisture anomalies; future studies could include root-zone moisture if deeper soil contributions are significant.

Despite these limitations, the results underscore the need for sustainable water resource management in Saudi Arabia. The current rate of groundwater decline is unsustainable and risks long-term ecological and economic consequences. Policymakers could benefit from integrating

GRACE-based monitoring into national water accounting systems, especially given the country's ambitious Vision 2030 goals that include improving water efficiency and reducing reliance on nonrenewable aquifers.

5 Conclusion

This study demonstrates that Saudi Arabia has experienced significant groundwater depletion between 2002 and 2016, with an average loss rate of approximately -1.61 km^3 per year. By decomposing GRACE total water storage anomalies using independent estimates of surface water (PCR-GLOBWB) and soil moisture (GLEAM), we successfully isolated the groundwater storage component and confirmed it as the primary driver of long-term water loss in the region.

The analysis shows that neither surface water nor soil moisture trends can account for the observed decline, and that oil extraction plays no detectable role in the mass loss observed by satellite gravimetry. These findings underscore the importance of continued satellite-based hydrological monitoring and the urgent need for sustainable groundwater management strategies.

As Saudi Arabia moves toward water security goals under Vision 2030, tools like GRACE, combined with open-source hydrological models and remote sensing data, offer powerful means to assess and track invisible groundwater resources on national and regional scales.

References

[1] Climate Knowledge Portal, Saudi Arabia, `https://climateknowledgeportal.worldbank.org/country/saudi-arabia/climate-data-historical#:~:text=The%20average%20annual%20rainfall%20in,between%20400%20%E2%80%93%20600%20mm%20annually.`

[2] Ahmed Mohamed, Application of Time-Variable Gravity to Groundwater Storage Fluctuations in Saudi Arabia, 2022 (Frontiers in Earth Science)

[3] Global Forest Watch, Saudi Arabia `https://www.globalforestwatch.org/dashboards/country/SAU/`