Using satellite data to monitor Groundwater drought in the Algarve

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Summary

Groundwater drought presents significant economic and societal challenges, highlighting the need for effective monitoring and early warning systems at local and regional scales. Despite its vital role in water supply and irrigation, groundwater drought is often not adequately monitored in national operational systems. While the propagation of meteorological drought through hydrological systems has been extensively studied in various parts of the world, there is a lack of groundwater drought monitoring at an integrated basin-scale based on groundwater data. Long-term hydrological drought is often assessed using meteorological drought indices like SPI or SPEI with long periods of accumulation (12, 24 or 48 months time scales). However, most studies recognize that the accumulation periods necessary to achieve maximum correlation with groundwater observations exhibit high spatial variability due to the complexity of local hydrogeological conditions. This study aims to address this gap on groundwater drought monitoring in the Algarve by investigating the suitability of GRACE-based drought indices and ground-based drought indices derived from piezometer measurements for monitoring and predicting groundwater droughts.

We first evaluate the performance of several GRACE products using a water budget analysis based on precipitation, evapotranspiration and runoff obtained from public databases and re-analysis datasets. The aim is to determine which GRACE solution provides the best closure of the water budget first in Iberia and then in the Algarve. Then, we examine the match between GRACE-derived groundwater storage and in-situ groundwater level measurements obtained from a set of 51 piezometers, distributed across 12 aquifers. Among the 5 GRACE products tested in this study, the one that produces the best fit to the closure of the water budget in Iberia is the CSR Mascon. It is concluded that GRACE provides a consistent representation of the hydrological cycle and thus, can be used as an aid in monitoring climate-related water mass transports in the Algarve region.

Assessment of GRACE products

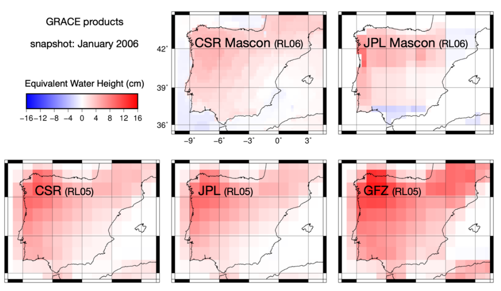


Figure 3 Example of a snapshot (January 2006) of the five different GRACE products over Iberia showing differences in spatial resolution and range of Total Terrestrial Water Storage (ΔTWS). The solutions represent total water storage anomalies expressed in units of equivalent water height (in cm).

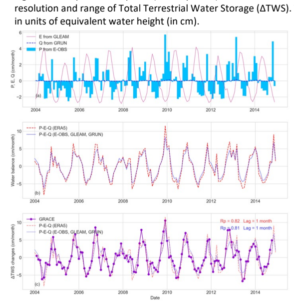


Figure 4 (a) Components of the water budget over Iberia: precipitation P, evapotranspiration E and runoff Q. (b) Two estimates of the water budget: P-E-Q from E-OBS,GRUN, GLEAM and the same from ERA5. (c) Time changes in TWS from GRACE (CSR-M) compared to the water budget.

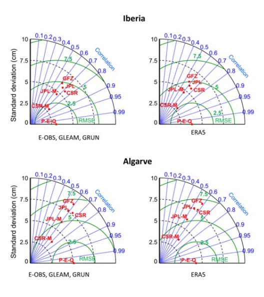
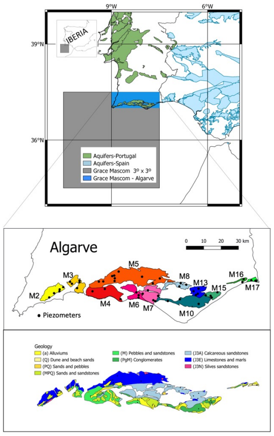


Figure 5 Taylor diagrams showing the correlation coefficients, standard deviations and root mean square errors (RMSE) between TWS from GRACE products and the two independent estimates of the water balance, for Iberia and for the Algarve region.

Study area



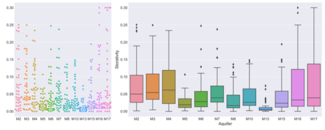


Figure 2 Statistical distribution of the storativity estimates for aquifers M2 to M17. Boxes represent median, quartile and extreme values. Outliers are a function of the inter-quartile range.

Table 1 Studied aquifers in the Algarve

Code	Name	Type	Area (km²)	N. of wells
M2	Almadena - Odeaxere	Semi-confined karst	63.489	5
M3	Mexilhoeira Grande - Portimao	Semi-confined karts and porous	51.707	5
M4	Ferragudo - Albufeira	Semi-confined karst and porous	117.099	3
M5	Querenca - Silves	Semi-confined karst	317.839	11
M6	Albufeira - Ribeira de Quarteira	Semi-confined carbonate	54.546	3
M7	Quarteira	Semi-confined karst and porous	81.185	5
M8	S. Bras de Alportel	Semi-confined karst	34.425	3
M10	S. Joao da Venda - Quelfes	Semi-confined carbonate	113.305	3
M13	Peral - Moncarapacho	Semi-confined karst	44.066	4
M15	Luz - Tavira	Semi-confined karst and porous	27.720	5
M16	S. Bartolomeu	Semi-confined karst and porous	10.595	2
M17	Monte Gordo	Unconfined porous	9.616	3

Figure 1 Location of the study area. Map of southwest Iberia showing the groundwater bodies in Portugal and Spain, the 3° x 3° cell grid of the GRACE Mascon JPL product and its extent over land coinciding with the Algarve region. The zoomed region shows the studied aquifers systems (M2 to M17) in the Algarve and the location of the in-situ monitoring wells (black dots). The bottom map shows the surface geology of the studied aquifers.

GRACE versus Groundwater data

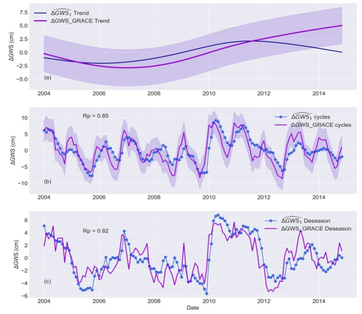


Figure 6. (a) Trend, (b) Seasonal and (c) De-seasonalized components (annual cycle removed) of ΔGWS derived from GRACE and the spatially averaged Groundwater Storage changes computed from the 51 piezometers in the Algarve region. GRACE error in in light shading and Rp indicates the Pearson's correlation coefficient between time-series.

In semi-arid regions the water storage measured by GRACE can be partitioned into changes in groundwater storage (ΔGWS) and changes in soil moisture (ΔSM)

$$\Delta GWS = \Delta TWS - \Delta SM$$

In order to compare ΔGWS derived from GRACE with in-situ observations, it is necessary to convert groundwater levels measurements into groundwater storage changes

$$\Delta GWS_{observed} = S\,\Delta h$$

Where S is the storativity (dimensionless) and Δh are the changes in hydraulic head observed in-situ.

	Original time-series	Seasonal components	De-seasonalized
M2	0.62	0.75	0.78
M3	0.67	0.83	0.75
M4	0.87	0.85	0.76
M5	0.78	0.75	0.81
M6	0.75	0.76	0.75
M7	0.8	0.75	0.73
M8	0.74	0.72	0.59
M10	0.78	0.81	0.77
M13	0.54	0.66	0.51
M15	0.66	0.72	0.66
M16	0.51	0.78	0.76
M17	0.58	0.83	0.8

Table 2 showing the Pearson's correlation coefficients computed between GRACE and in-situ total, seasonal and residual components at individual aquifers, in the form of a heat map. It provides a direct overview of which aquifers are the ones where GRACE has the greatest potential for being used as a complementary tool of groundwater storage monitoring. Aquifer M4 stands out as the aquifer whose fluctuations are best captured by the satellite in the time span of this study.

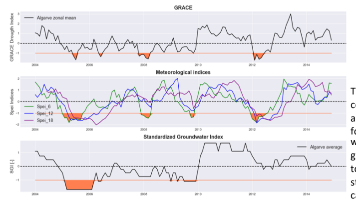


Figure 7. Drougth indices in the Algarve region computed from spatially averaged datasets (GRACE, SPEI-6, -12 and -18 based on ERA5 precipitaton and evapotranspiration, and in-situ groundwater levels at the 51 piezometers in the Algarve)

Conclusions

This study tested GRACE not as an alternative but as a complementary tool to the existing in-situ network. It demonstrated the feasibility of GRACE for estimating regionally integrated changes in groundwater storage, capturing multi-year deficits and surpluses, and identifying wet and dry periods. GRACE effectively detected major droughts and anomalously wet years in the region. Additionally, it performed well in detecting local deviations from the regional average at the aquifer level. However, estimating groundwater drought is highly specific to each site. The Groundwater drought index is a strong function of piezometric record autocorrelation, and the appreciation of drought conditions requires a thorough understanding of the hydrogeological context at each observation site.

Recommendations

Given the significant contribution of groundwater over-abstraction to aquifer depletion during droughts, it is recommended to find ways to identify over-abstraction from space. While GRACE-based indices offer basin-integrated estimates and can overcome some observational limitations, complementary higher-resolution products as well as local validation remain crucial.

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