GROUNDWATER MANAGEMENT

From space to soil: Tracking South Africa's shrinking water reserves

TrigNet vs GRACE/-FO – How can ground-based GNSS stations and satellite-based gravity measurements be used to monitor droughts and groundwater depletion? Article by Sue Matthews.

A somewhat surprising effect of climate change was recently reported by local and international media, following a press release issued in April by the University of Bonn in Germany. Titled "Climate change is lifting South Africa out of the ocean", it claimed that droughts and the associated water loss caused the country to rise by 6 mm between 2012 and 2020.

The press release marked the publication of a paper by Mielke et al. in the ***Journal of Geophysical Research: Solid Earth***. This had the far less sensationalist title "GNSS observations of the land uplift in South Africa: implications for water mass loss", referring to data from the national network of continuously operating Global Navigation Satellite System base stations. Known as TrigNet, it came into operation in 1999, providing Global Positioning System (GPS) data that is used not only for surveying and mapping but also for research and monitoring of atmospheric water vapour, space weather and movements of the Earth's crust.

Recent studies by Hammond et al. (2021) and Gourley and Harig (2024) have used the data to show that the land surface in many regions of South Africa has been rising at a rate of up to 2 mm per year. These authors attribute the uplift either to dynamic topography – the interaction between the Earth's hard outer shell, or lithosphere, and the hot, slow-flowing rock of the mantle below – or to a plume of buoyant material upwelling from the deeper parts of the mantle. The mantle plume was hypothesised in 1985 by the late Dr Chris Hartnady, then of the University of Cape Town's geology department and later known to many in the water research field through his work at Umvoto, the consultancy founded by his partner, Dr Rowena Hay. He identified its likely location in the Lesotho–KwaZulu-Natal region and named it the Quathlamba hotspot after the Zulu name for the Drakensberg, uKhahlamba, meaning "barrier of spears". More than three decades later, Gilfillan et al. (2019) reported that the isotopic composition of gas samples collected from natural carbon dioxide seeps along the Ntlakwe-Bongwan fault in

KwaZulu-Natal confirms the existence of the Quathlamba mantle plume.

The German research team proposes an alternative explanation for the observed uplift, believing that it is the elastic response of the crust to reduced surface mass load resulting from water loss during droughts. To arrive at this conclusion, they initially downloaded GPS height time series for 102 GNSS stations but excluded 14 that recorded less than three years of data. Singular spectral analysis was then used to separate long-term trends and annual and semi-annual signals from noise for the remaining 88 stations. Of these, only 57 stations were used for further data analysis, the rest being excluded because they showed unusual motions compared to neighbouring stations. The vertical motion determined from the processed GPS height time series was inverted into point mass loads to model changes in total terrestrial water storage (TWS), according to a method developed by other researchers more than a decade ago.

The resulting TWS changes were validated with those in the Global Land Water Storage (GLWS) version 2 dataset, which is produced by assimilating TWS changes derived from GRACE/-FO into the WaterGAP Hydrology Model. GRACE/-FO refers to the Gravity Recovery and Climate Experiment satellite mission, operational from April 2002 to July 2017, and its successor, GRACE Follow-on, which began providing data in June 2018. A second validation step was done with TWS data derived from the Global Land Data Assimilation System Noah (GLDAS-Noah) model, which does not include GRACE/-FO data as an input. The validation exercise revealed a correlation of 46% between GPS- and GLWS-derived TWS and 53% between GPS- and GLDAS-Noah-derived TWS, but a much stronger correlation of 84% when GPS-derived TWS was compared with the original GRACE/-FO solution used for the GLWS computations.

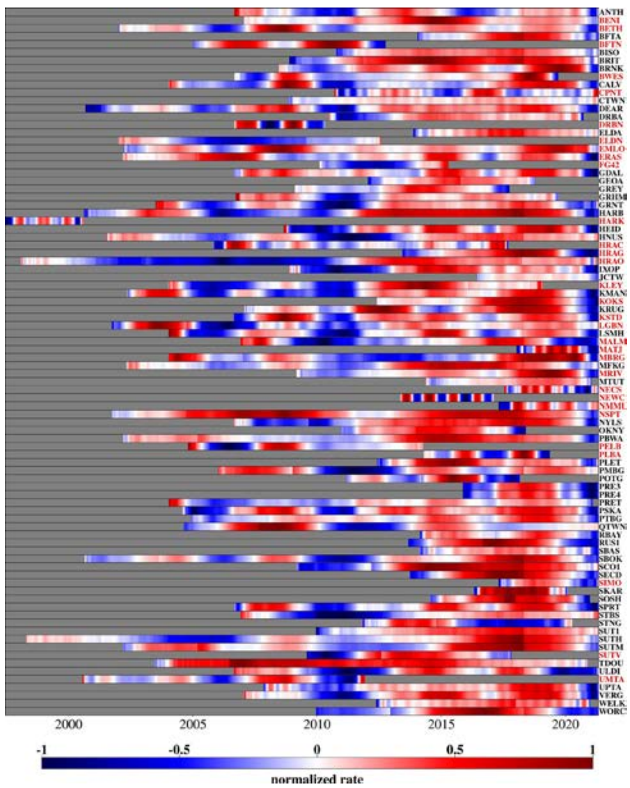
In analysing long-term trends in all three datasets, the team observed an increase in TWS during the 2011 and 2021 La Niña events and a decrease with the onset of dry periods in 2015 around the El Niño event. In total, the GPS-derived TWS exhibited a net mass loss of −71.3 mm over the entire period from September 2000 to April 2021.

Similar studies have been done elsewhere in the world, where the network of GNSS stations is denser and more evenly spread, but the research team notes that it's clear from their findings that seasonal and long-term hydrological changes can be measured even with limited GNSS coverage. "The TrigNet GNSS network in South Africa, originally set up for engineering projects, has great potential for hydrological applications such as estimating the impact of drought on water resources, especially if the network is expanded to cover more areas. For example, regions in the northwest of South Africa, such as the Northern Cape and North West, could particularly benefit from hydrogeodesy if GNSS sites are installed there," they conclude.

According to Richard Wonnacott, who was instrumental in establishing and developing TrigNet before he retired as Director of Survey Services at the Chief Directorate: National Geo-Spatial Information (CD: NGI) in 2013, the reliability of the network has been remarkably good since its inception and is now at about 95% or better, given that telecommunication links relying on copper wire have been replaced by fibre optic and other modern technologies. GNSS data is streamed to the central control station at CD: NGI at one-second intervals, 24 hours per day and 365 days per year, and processing of this data allows horizontal and vertical land movements to be estimated to a very high level of accuracy and precision.

The research team points out that GNSS data can complement GRACE/-FO data, which is only accessible months after capture, has limited spatial resolution and is subject to several sources of error. The GRACE/-FO satellite mission is particularly special because it is the first and only one that allows for groundwater monitoring, but there are additional uncertainties when deriving groundwater storage changes from the TWS data. This is because TWS is the sum of all water storage in snow, ice, lakes, rivers, dams, wetlands, canopy water, soil moisture and groundwater. Extracting the groundwater data requires estimating all the other components using models, other satellite data or available field data, and then subtracting them from the TWS.

In fact, GRACE/-FO does not even measure TWS directly, but rather variations in the Earth's gravity field. And, unlike most satellite missions, its observations are not based on measurement of reflected or emitted wavelengths in the electromagnetic spectrum, which would only be useful for water in the first few centimetres below the land surface. Instead, GRACE/-FO relies on twin satellites orbiting the Earth about



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Normalised daily vertical displacement rates (rate-gram) for all GNSS stations derived from the long-term trend using singular spectrum analysis (SSA), where red = rising; blue = sinking. The rise was particularly pronounced during the drought between 2015 and 2019. Station names in red, which showed unusual motion compared to neighbouring stations, were excluded when modelling terrestrial water storage. From Mielke et al., 2025. https://doi.org/10.1029/2024JB030350

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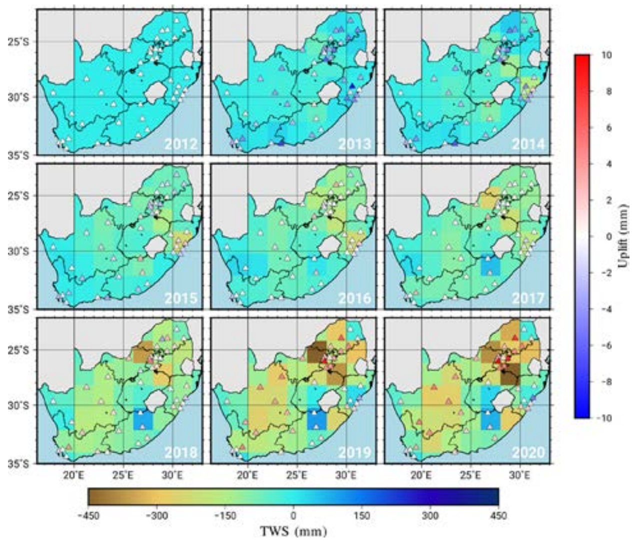

Mean annual variations in GPS-derived terrestrial water storage and land uplift at GNSS sites, both relative to the mean of 2012. The browner the region, the higher the water loss. Red triangles represent GNSS sites that had risen in height since 2012. From Mielke et al., 2025. https://doi.org/10.1029/2024JB030350

220 km apart, with the exact distance between them being measured every few seconds as each experiences a stronger or weaker gravitational pull due to surface mass changes. This and other data are used by three different processing centres in the United States and Germany – each using their own algorithms to generate different solutions – to produce monthly maps of the Earth's gravity field. With further processing, gravity field changes from month to month are used to produce monthly maps of TWS anomalies, representing a deviation from a long-term mean.

The spatial and temporal resolution of GRACE/-FO data products – 200 000 km^2 and monthly respectively – limits their usefulness for local application and short-term events, although various downscaling methods have been developed to improve resolution. These typically involve integrating the data products with higher-resolution datasets or using models, statistical interpolation or machine learning algorithms.

In South Africa, a number of projects using GRACE/-FO for groundwater-related research have been undertaken to date.

- Zaheed Gaffoor and colleagues conducted a study that was funded by a multi-agency coalition and published in February 2021 as the Water Research Commission report ***Big data analytics and modelling – localising transboundary data sets in southern Africa: a case study approach (WRC report no. TT 843/20)***, http://bit.ly/4nmJDMX. The main aim of the research was to investigate the use of big data analytics to integrate, match and model groundwater data to improve sustainable groundwater management at the local scale. GRACE/-FO-derived groundwater storage anomalies were one of nine hydroclimatic parameters used in a machine learning model to predict 30-day groundwater level changes at ~5 x 5 km resolution across two case study areas: the Zeerust/Lobatse/Ramotswa karstic dolomite aquifers in North-West Province and Gauteng, extending into Botswana, and the Shire Valley alluvial aquifer straddling the border between Malawi and Mozambique. The case studies were used for two papers published in 2022 in *Hydrogeology Journal* and *Hydrology* respectively, which formed part of Gaffoor's PhD thesis submitted to the University of the Western Cape.

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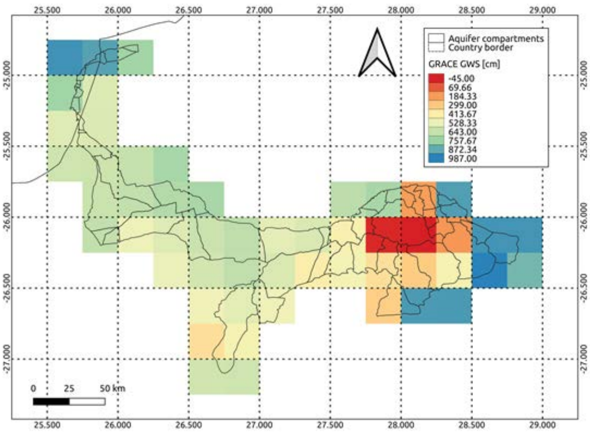

Net GRACE-derived groundwater storage anomaly 2002-2020 for the Zeerust/Lobatse/Ramotswa dolomite aquifers, compared to the baseline period 2004–2009. From Gaffoor et al., 2021. WRC Report No. TT 843/20.

- Khuliso Masindi explored the potential of GRACE/-FO data in his PhD thesis, 'Water resources modelling in the Vaal River Basin: an integrated approach', for which he was awarded his degree by the University of the Witwatersrand. In a May 2021 webinar, available on the Ground Water Division's YouTube channel, he emphasised that GRACE/-FO data is used for estimating changes in groundwater storage rather than groundwater storage itself, which would require an understanding of the aquifer properties, and there must be a significant mass movement of water for anomalies to be detectable. Although GRACE/-FO data is best applied in areas exceeding 200 000 km^2, the Vaal River Basin is 197 513 km^2, yet the results yielded no clear relationship between GRACE/-FO-derived groundwater storage change and total rainfall, annual rainfall anomaly, surface water storage or soil moisture. Nevertheless, GRACE/-FO-derived groundwater storage had shown an increase of 3.31 km^3 per year over the period 2003–2014, and the drivers of this increase were probably the input of above-average rainfall events and induced recharge by the big dams in the area. Masindi noted that the GRACE/-FO-derived groundwater storage change was not validated with groundwater level data due to data scarcity, and concluded by stressing the need to continue field-based monitoring to collect this and other hydro-meteorological data.

- Manish Ramjeawon and co-authors used GRACE/-FO data to analyse groundwater storage change in the primary and secondary aquifers of the Usutu-Mhlatuze Water Management Area in northern KwaZulu-Natal. The main primary aquifer is located on the Maputaland coastal plain, where streams, lakes and wetlands are groundwater dependent to varying degrees, while the secondary aquifers occur further inland. An initial validation exercise for the period 2010 to 2016 showed good agreement between GRACE/-FO-derived groundwater storage anomalies and in-situ groundwater storage anomalies determined from observation borehole data, so GRACE/-FO data was used for the full study period between 2002 and 2020. The results indicated that groundwater storage increased relative to the 2004–2009 mean during the period 2002–2014 and then declined drastically during the period 2014–2020. The water level of Lake Sibayi had dropped markedly by 2020, and the areal coverage of other wetlands and waterbodies on the coastal plain had decreased significantly. The groundwater storage loss and the associated impact on surface water systems was attributed to a change in land use – particularly the rapid expansion of commercial forestry plantations – combined with groundwater abstraction and regional climatic changes, evident as increased evaporation and evapotranspiration and decreased precipitation. The research was published in the *Journal of Hydrology: Regional Studies* in 2022 and was the basis of Ramjeawon's PhD thesis submitted to the University of KwaZulu-Natal.

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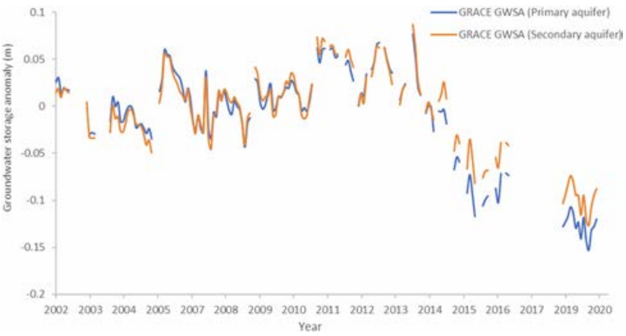

GRACE derived groundwater storage anomalies for the primary and secondary aquifers of the Usutu-Mhlatuze Water Management Area between 2002 and 2020 relative to the baseline mean (2004 –2009). From Ramjeawon et al., 2022. https://doi.org/10.1016/j.ejrh.2022.101118

- Ritshidze Nenweli evaluated GRACE/-FO data to assess groundwater storage during droughts in the Western Cape for her MSc degree, awarded by Stellenbosch University in 2023, and published the research with co-authors in the *Journal of Hydrology: Regional Studies* in 2024. In-situ data on groundwater storage variations in 12 of the province's aquifers were compared with that from both GRACE/-FO and GLDAS, which integrates satellite and ground-based data using advanced land surface modeling and data assimilation techniques. For GRACE/-FO data, the highest positive correlation (***r*** = 0.69) was found between GRACE/-FO-derived TWS anomalies and in-situ groundwater storage variations in the Adelaide Subgroup Aquifer. This is an unconfined aquifer with an areal extent of 194 000 km² – close to GRACE/-FO's recommended resolution of 200 000 km². GRACE/-FO-derived groundwater storage anomalies combined with soil moisture changes from the GLDAS Catchment Land Surface Model (CLSM) had the greatest correlation (***r*** = 0.52) with in-situ data from the Bokkeveld Aquifer. The strongest correlations were found between GLDAS-based groundwater storage anomalies and groundwater storage variations in the unconfined Table Mountain Group Upper Aquifer Unit (***r*** = 0.83) and Cape Flats Aquifer (***r*** = 0.73).

In addition to these studies, several papers by international research teams address the use of GRACE/-FO data to monitor groundwater in Africa's largest aquifers, including the Main Karoo Basin in South Africa.

In conclusion, the integration of ground-based GNSS stations like TrigNet and satellite-based systems such as GRACE/-FO presents a powerful approach to monitoring groundwater depletion and drought impacts in South Africa. While GRACE/-FO provides invaluable large-scale insights into terrestrial water storage, its spatial and temporal limitations highlight the complementary role that GNSS data can play in offering higher-resolution, real-time measurements. The growing body of local research using these technologies demonstrates both their current value and future potential for water resource management.

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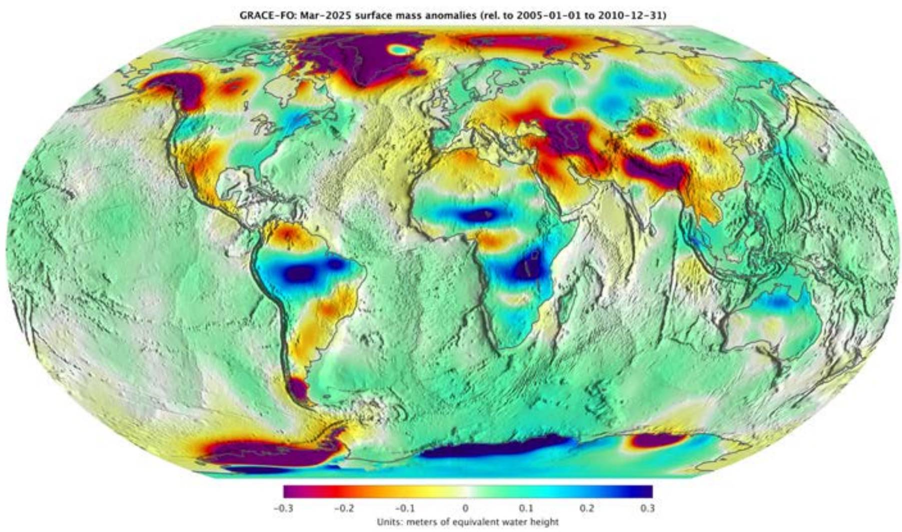

Global surface mass anomalies observed by the GRACE-FO satellites for March 2025. Over land, red indicates below-average terrestrial water amounts, while blue shows above-average water amounts. Over oceans, red indicates below-average ocean bottom pressure, while blue shows above-average bottom pressure. Ocean bottom pressure changes are related to large-scale ocean current variations, as well as overall sea level changes from ocean mass changes.