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Is groundwater running out in the Western Cape, South Africa? Evaluating GRACE data to assess groundwater storage during droughts

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ABSTRACT

Study region: The Western Cape (WC), South Africa.
Study focus: The WC has become increasingly dependent on groundwater in recent years due to repeated droughts. A framework to monitor the regional groundwater levels is urgently required to sustainably manage the WC's water resources, since the region has inconsistent or unavailable monitoring data. Therefore, this study aims to understand how Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) data can be used to monitor groundwater storage variations (ΔGWS) in the WC. In-situ ΔGWS time-series from twelve aquifers in the WC were compared to GRACE and GLDAS data.
New hydrological insights for the region: GRACE terrestrial water storage anomalies (ΔTWS) showed moderate positive correlation ($r = 0.69$) with in-situ ΔGWS from the Adelaide Subgroup Aquifer (ASA), an unconfined aquifer with large areal extent and large ΔGWS. The Table Mountain Group Upper Aquifer Unit (TMG UAU) and Cape Flats Aquifer (CFA) also showed significant positive correlations with GLDAS ΔGWS of 0.83 and 0.73, respectively. Our results suggest that ΔGWS in the ASA can be monitored using GRACE ΔTWS, while GLDAS ΔGWS data can be used to monitor ΔGWS in the unconfined TMG UAU and CFA. GRACE and GLDAS data may be suitable to monitor groundwater availability in other water- and data-scarce regions of Africa.

1. Introduction

Droughts are projected to become more severe and intense across many regions of the world (Qi et al., 2022). Groundwater resources are often relied upon during periods of drought to compensate for diminished and unreliable surface water supplies (Department of Water Resources DWR, 2015). Groundwater played a crucial role as a source of water in Southeast Asia (Shivakoti et al., 2019), Brazil, and Australia (Famiglietti, 2014) during droughts. Due to the growing demand for water (Viljoen and van der

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Walt, 2018), there is an urgent need for a monitoring system to properly manage groundwater resources. Continuous regional groundwater data measurements can make it easier to monitor the availability of groundwater resources and to guarantee its long-term use. However, the expense of setting up and keeping instrument networks up to date, the presence of gaps in those monitoring networks, as well as the failure to digitize and share the data, makes it challenging to assess variations in the hydrologic conditions at a larger scale (Rodell et al., 2015).

Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) can be used for groundwater storage (GWS) evaluations in data-poor areas of the world (Rodell et al., 2007). Observations from GRACE satellite missions show that the rate of groundwater depletion in the California's Central Valley has been accelerating since 2003 (1.86 km^3 /yr, 1961–2021; 2.41 km^3 /yr, 2003–2021; 8.58 km^3 /yr, 2019–2021), a period of megadrought in southwestern North America (Liu et al., 2022). In South Africa groundwater resources are essential for the survival of approximately 80% of the country's rural inhabitants due to the lack of water infrastructure (Nkuna et al., 2014). Groundwater monitoring and management is important to ensure its availability from increasingly intense droughts.

In South Africa, droughts are common, and in recent years (since 1900) there has been a growing tendency towards more multi-year droughts (Baudoin et al., 2017; Gibberd et al., 1995; Jordaan, 2017). A severe drought occurred in the Western Cape province between 2015 and 2018, which led to its designation as a disaster region in February 2018 (Burls et al., 2019; Mahlalela et al., 2019; Pienaar and Boonzaaier, 2018; Sousa et al., 2018). Other major droughts in the Western Cape occurred from 2003–2006, 2009–2011, and 2017–2019 (Adams et al., 2018; Araujo et al., 2016; Botai et al., 2017; Theron et al., 2021; Visser, 2021). Most of the winter-rainfall zones were severely influenced by the 2015 to 2018 drought (Archer et al., 2019; Conradie, 2018), which was the most severe drought recorded from 1988 to 2018 at five of the six stations (Theron et al., 2021) and contributed to fires which burned ~ 25, 000 ha, contributing to ~R40 million (USD 2 174,800) damage (Isaacs, 2017). Prior to this drought, the City of Cape Town relied almost solely on surface water. The dry conditions that began in January 2015, peaked between May 2017 to June 2018, when collective dam water levels of the Western Cape Water Supply System (WCWSS) hovered around 20% of the total reservoir capacity (Fig. 1). In late 2017, this crisis triggered the Department of Water and Sanitation (DWS) to impose severe water-use restrictions in many major cities in the Western Cape in preparation for a potential 'Day Zero' scenario. Day Zero referred to the case where all private taps supplied by the WCWSS would be shut-off due to insufficient water supply (Baudoin et al., 2017; Botai et al., 2017). Fortunately, 'Day Zero' never arrived and the water levels within the WCWSS have since recovered from rainfall in the 2018 to 2021 winter months (Fig. 1).

'Day Zero' highlighted the importance of sustainably managing water resources in the Western Cape, as well as demonstrating the over-reliance on surface water. An increase in water demand brought on by population increase and the growth of irrigated agriculture augmented the water deficit (City of Cape Town, 2022a, 2022b; Parks et al., 2019). DWS decided to limit agricultural reservoir releases to mitigate the consequences of meteorological deficits, forcing farmers to rely on groundwater (Watson et al., 2022). Consequently, major reductions in water use came from the agricultural sector (Isaacs, 2017). Citizens also reduced water use, reused grey water, harvested rain water, and increasingly started to tap into groundwater for their needs irrespective of whether the hydrogeology was considered favourable (Conrad et al., 2019). Some local hydrogeologists believe that groundwater enabled the municipalities, residents, and industries of the Western Cape to avoid a Day Zero (Barrow, 2020; Parsons, 2022).

Recent climate modelling suggests that the 2015 to 2018 rainfall deficit will be five to six times more likely in the future due to anthropogenic activities driving climate change (Pascale et al., 2020). Thus, groundwater may be able to serve as a sustainable water source to increasing drought resilience in the Western Cape (Conrad et al., 2019). However, the response of GWS at the provincial scale has not yet been evaluated, despite data on surface water usage and reservoir storage levels being readily available (CCT, 2023). Therefore, unmonitored and unregulated abstraction of groundwater, especially under unstable climatic conditions, is a significant threat to the Western Cape's water security.

In recent years, both GRACE, a remote sensing observation from the American National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) collaboration, and GLDAS, have been widely used to evaluate groundwater storage changes (ΔGWS) in many areas (Bhanja et al., 2016; Dubey et al., 2021; Huang et al., 2016; Kruy and Ruangrassamee, 2022; Melati

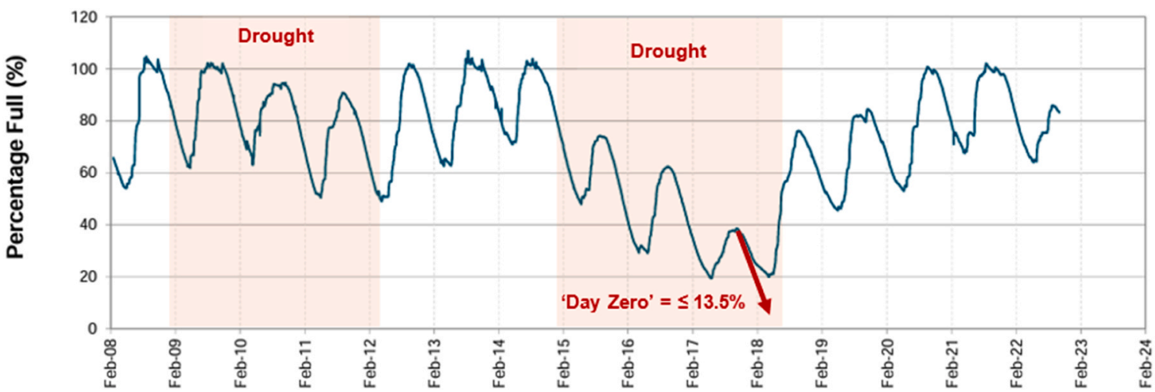

Fig. 1. Total water stored in the WCWSS reservoirs (modified after: (CCT, 2022).

et al., 2019; Neves et al., 2020; Ramjeawon et al., 2022; Rodell et al., 2007; Thomas et al., 2015). GLDAS is a NASA project that aims to produce optimal fields of land surface states and fluxes by combining satellite and ground-based observational data products with progressive land surface modeling and data assimilation methods (Rodell et al., 2004). Bhanja et al. (2016) combined GRACE terrestrial water storage changes (ΔTWS) and GLDAS land-surface modelled soil moisture to estimate ΔGWS and compared it with over 15,000 groundwater observation wells connected to a combination of three distinct land-surface models across 12 major river basins in India. These land-surface models included the Variable Infiltration Capacity models (VIC), National Centers for Environmental Prediction (NCEP)/ Oregon State University/Air Force/Hydrologic Research Lab (NOAH) Model and Community Land Model (CLM). Results revealed a significant correlation in more than 50% of the basins (Bhanja et al., 2016).

Similarly, a comparison was made between groundwater levels, and GRACE ΔTWS and ΔGWS in Alberta, Canada, demonstrating the feasibility of using remotely sensed estimates to map ΔGWS in this region of varying geologic setting (shallow Quaternary-Neogene aquifers and deep sedimentary basin), comparing results against data from a well-established groundwater-monitoring network—the Groundwater Observation Well Network (GOWN) (Huang et al., 2016). These investigations, along with a number of others (Castle et al., 2014; Famiglietti et al., 2011; Gonçalvès et al., 2013), highlight the fact that GRACE outputs can offer an effective method of assessing ΔGWS in locations that are not well gauged.

Dubey et al. (2021) assessed the long-term groundwater variation in India using GLDAS-2.2 products and concluded that GWS was on a declining trend from 2003 to 2019. Kruy and Ruangrassamee (2022) examined monthly ΔGWS over the Greater Chao Phraya River Basin in Thailand from 2009 to 2018 using GWS data from GLDAS-2.2. They found a strong positive correlation (> 0.7) between GLDAS ΔGWS and in-situ ΔGWS, concluding that GLDAS has a potential to monitor shallow ΔGWS of the basin.

Data from the literature demonstrate the potential benefit of using methods that combine GRACE and GLDAS data products for regional groundwater assessments in data-deficient regions of the world (Kruy and Ruangrassamee, 2022; Rodell et al., 2007). In this respect, the Western Cape province is a suitable option for the application of GRACE and GLDAS derived data to analyse changes in GWS, where preliminary analysis of scattered in-situ groundwater level observations throughout the Western Cape showed both a declining and a rising trend in GWS (Fig. A1.1a-l) Therefore, this study aims to investigate if GRACE and GLDAS data can be used as a tool for monitoring GWS changes in the Western Cape, providing guidance on expanding this knowledge to other data-sparse aquifer systems in Africa.

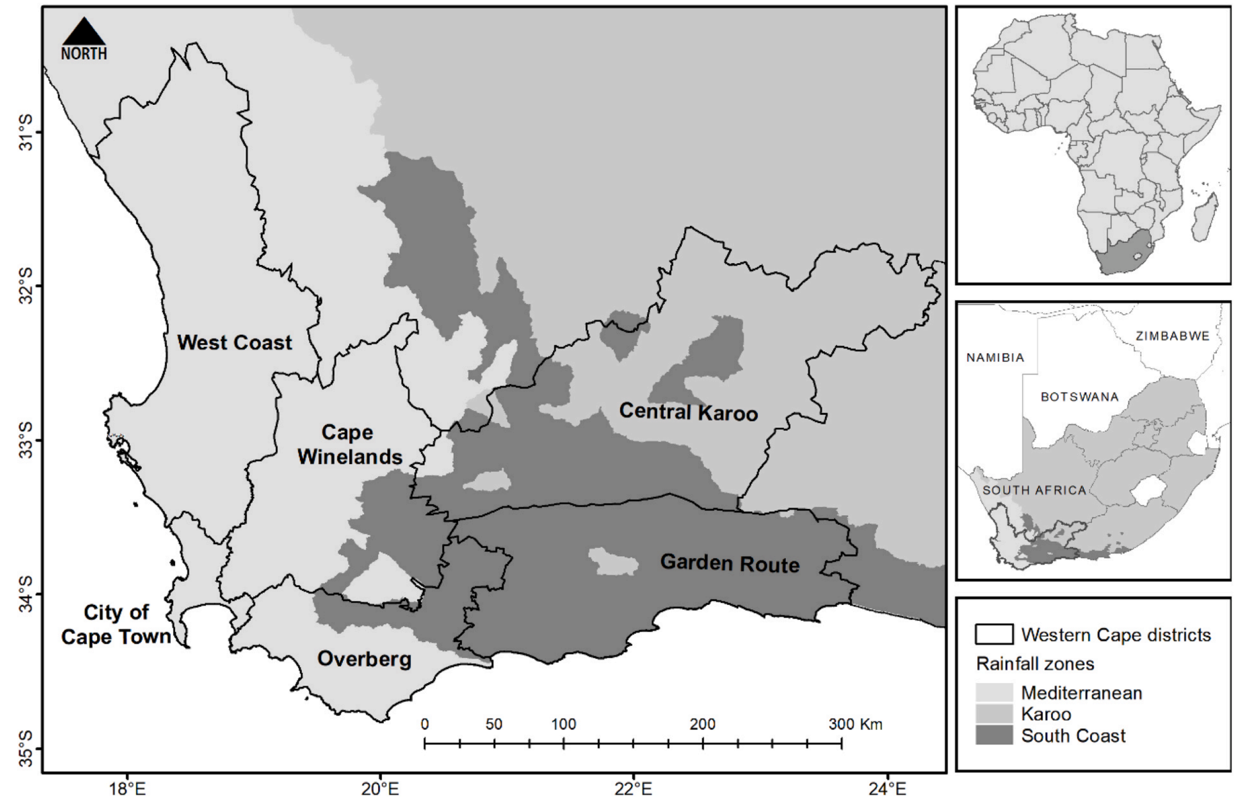

Fig. 2. The main districts of the Western Cape province and its three distinct rainfall zones (South Africa).

2. Description of study area

2.1. Location

The Western Cape province (Fig. 2) is situated in the south-western tip of South Africa. It has an areal extent of 129 462 km^2 (YM, 2012) and a population of 7.1 million persons (City of Cape Town, 2022a, 2022b). Its surface area makes it the fourth largest province in South Africa, it also ranks fourth in population. Inside the province are five district municipalities (Central Karoo, West Coast, Garden Route, Overberg and Cape Winelands) and the City of Cape Town Metropolitan Municipality.

2.2. Rainfall

The Western Cape is the only province in South Africa which receives winter rainfall (May-Aug). Rainfall varies greatly, with average annual rainfall as high as 3345 mm/a in the mountainous areas of the Cape Winelands District; and a minimum of 60 mm/a in the Central Karoo District (Diamond, 2014). Most areas receive between about 200 mm/a and 1 000 mm/a (Mahlalela et al., 2019). The Western Cape province is characterised by three main rainfall regions namely the Mediterranean, South Coast and Karoo regions (Fig. 2, Botai et al., 2017; du Plessis and Schloms, 2017). The City of Cape Town, which is situated in the province's south-western corner, is categorized as having a Mediterranean-type climate, characterised by cool, rainy winters and warm, dry summers, with an average annual rainfall of 515 mm (CSIR, 2014). Regions in the South Coast experience rainfall all year-round, whereas the Karoo regions experience late summer rainfall. The rainfall is highly variable across the Central Karoo, with $<$ 100 mm per annum recorded in the north – western Karoo and increasing to approximately 400 mm/a along the eastern parts of the Karoo (Willis, 2014). The Western Cape's groundwater recharge can be as high as 811 mm/a (WCDoA, 2022), especially in mountainous areas, while the lowest recharge are in flat areas, such as in the northern West Coast District and Central Karoo District (WCDoA, 2022).

2.3. Hydrogeological setting

Typical aquifer types in the Western Cape are fractured, intergranular, intergranular and fractured, and karstic (Fig. 3, Department

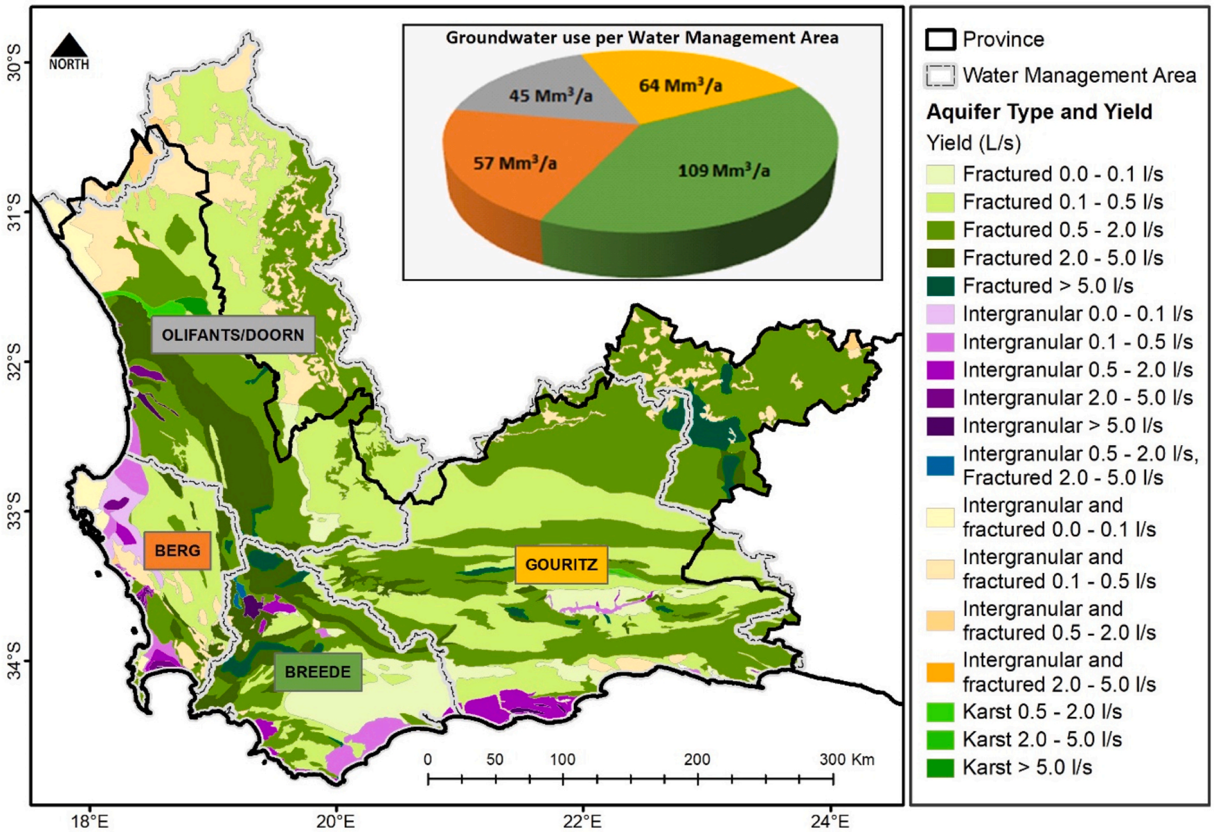

Fig. 3. Main aquifer types in the Western Cape (After: WCDoA, 2022) and groundwater use for each water management area (Mm^3/a, data Source: Adam et al., 2018). Coloured labels of the water management areas correspond with the inset pie graph of groundwater use.

Table 1
Physical properties of aquifers in the study area.

Aquifer type	Aquifer Unit	Area (km^2)	Rainfall (mm/a)	Recharge (Mm^3/a)	Volume stored (Mm^3)	Transmissivity (m^2/d)	Storativity [-]	Yield (L/s)	Ref
Fractured	TMG	37,000	163.51 – 1842.06	260 – 2 600	900 – 66,000	0.359 – 400	10^{-3}	> 5	(Lin, 2007; Mohuba et al., 2020)
	Bokkeveld	28,000	< 6	NA	NA	23 – 110	1×10^{-3} – 3.5×10^{-5}	< 1 - > 5	(Maherry et al., 2009; Rosewarne, 1981)
	Adelaide Subgroup	194,000	< 100 – 400	12	112	< 10 - > 100	1×10^{-2} – 1×10^{-6}	0.1 - > 5	(Campbell, 1980; Rose, 2017; van Wyk and Witthueser, 2011)
Intergranular	Adamboerskraal	NA	320	25	1200	100 - 500	10^{-3}	< 0.5 - > 2	(Campbell et al., 1992; Meyer, 2001; Timmerman, 1985)
	Langebaan Road	NA	280	36	1235	100 - 1000	3.1×10^{-3}		
	Elandsfontein	NA	320	27	3150	300 - 600	3.6×10^{-4} - 10^{-3}		
	Grootwater	65	350 (220 – 700)	7.1	300	200 - 700	6.7×10^{-4} – 10^{-3}		
	Atlantis	130	369 - 465	11 - 16	413.05	NA	0.17 * *		(Campbell et al., 1992; Jovanovic et al., 2017)
	Cape Flats	630	509 (344-751)	5 - 60	1500	50 – 650	0.2 * *		(DWAF, 2008)
Karst	Vanrhynsdorp*	4 000	NA	NA	NA	NA	10^{-2}	0.5 – 2 & > 5	(Dennis and Dennis, 2012; Department of Environmental Affairs and Development Planning DEAandDP, 2011; DWAF, 2006)

of Environmental Affairs and Development Planning DEAandDP, 2011; Jonck and Meyer, 2002). Table 1 summarizes the physical properties of the aquifers in the study area (see Table A2.1 detailed version of Table 1 and Table A2.2 for the hydrogeochemistry in Supporting Information). Fractured rock aquifers are by far the most dominant aquifers within the Western Cape, especially in the Gouritz WMA (94%) (Fig. 3 and Table A2.3). Groundwater use for each WMA is outlined in Fig. 3, where high exploitation is in the Breede WMA. Of the fractured aquifers, the Table Mountain Group (TMG) and Bokkeveld Aquifers (Fig. 5) are the most exploited; whereas the Witteberg, Karoo Supergroup (Ecca Group and Adelaide Subgroup), and Malmesbury can also yield water when fractured (Conrad et al., 2019). The Nardouw and Peninsula Aquifers are the two major semi-confined aquifers of TMG (Blake et al., 2010). The Nardouw Aquifer is used mostly to obtain groundwater for irrigation, while the Peninsula Aquifer necessitates deeper drilling (>200 m) and has only been utilized to a limited degree (Makiwane, 2019; Netili, 2007).

Intergranular (primary) aquifers also cover large areas of the Western Cape (Fig. 3) and vary in thickness (<10 m) (Department of Environmental Affairs and Development Planning DEAandDP, 2011). Three intergranular aquifer types can be distinguished, namely the Alluvial Deposits (consisting of gravel, sand, clay, silt or boulders), occurring primarily along various rivers (Meyer, 2001); the Bredasdorp and Sandveld (i.e., Adamboerskraal, Langebaan Road, Elandsfontein, Grootwater, Atlantis and Cape Flats Aquifers) Group Aquifers which are essentially coastal aquifers, consisting of clay, sand, pebbles and boulders.

The different granites are the only rocks that can be referred to as intergranular and fractured in the research area since groundwater appears in both weathered rock and jointed bedrock (Meyer, 2001). The Cape Granite Suite is the collective name for the granites within the study area. The Cape Granites are typically low yielding (~ 1 L/s) and these yields are only obtainable in highly weathered and faulted zones (Department of Environmental Affairs and Development Planning DEAandDP, 2011).

Within the Western Cape, karst aquifers are only present in the Olifants/Doorn and Gouritz WMAs with areal extent of 2% and 0.3%, respectively (Fig. 3, Department of Environmental Affairs and Development Planning DEAandDP, 2011). Groundwater levels within karst aquifers of the Olifants/Doorn WMA have been generally declining since 2013, suggesting the aquifers are stressed and that groundwater may be overexploited for agriculture (Department of Water and Sanitation DWS, 2015).

2.4. *Water supply and consumption*

The Western Cape is comprised of four Water Management Areas (WMAs), namely the Olifants-Doorn in the west, the Berg and the Breede in the south and the Gouritz in the east, and small section of the Fish to Tsitsikamma, east of the Gouritz (Fig. 3, Adams et al., 2018). While actual water consumption is matched with municipal boundaries (which overlaps WMAs), water resources are typically managed on a catchment scale, i.e., per WMA (Department of Environmental Affairs and Development Planning DEAandDP, 2011). Surface water is the primary water resource in all the four WMAs, and the primary water uses are irrigated agriculture, except for Berg WMA where main water uses are for urban and irrigated agriculture water use (Adams et al., 2018). The Berg WMA mostly serves the City of Cape Town and nearby urban areas. Where surface water is scarce, groundwater is often used for irrigation. The four Western Cape WMAs' groundwater consumption is highlighted in Fig. 3.

3. Methods

3.1. *Gravity Recovery and Climate Experiment (GRACE)*

The GRACE mission was initiated in March 2002 to map monthly gravity field of the Earth, which can be used to assess mass changes (assumed to be primarily water) on the planet (Landerer and Cooley, 2021). GRACE ran until October 2017 and was subsequently continued by GRACE Follow-On (GRACE-FO) mission in May 2018 (Landerer and Cooley, 2021; NASA, 2022). References made to GRACE will describe datasets from both GRACE and GRACE-FO missions.

We obtained changes in terrestrial water storage (ΔTWS) from the GRACE Jet Propulsion Laboratory (JPL) and Center for Space Research (CSR) at the University of Texas, Austin RL06 mass concentration (mascon) dataset from January 2003 to December 2020 (Landerer et al., 2020; Save, 2020; Save et al., 2016; Watkins et al., 2015; Wiese et al., 2019, 2016). Mascon solutions were used because they have less leakage, as land and ocean areas can be explicitly defined, and requires little to no postprocessing as opposed to spherical harmonics (Scanlon et al., 2016). Mascon solutions and Level-3 data products have the same physical meaning (Chao, 2016). The term "leakage" refers to the leakage-in signal from the outside regions, whereas the term "bias" (or "leakage-out") refers to the reduced signal for a target region (Huang et al., 2019; Longuevergne et al., 2010). The scaling factor method is one of the leakage correction methods used to restore signal lost during the filtering, i.e., process of removing noise from the raw GRACE data (Huang et al., 2019). The most recent release of Mascon solutions, RL06, from the CSR computing center is defined on a grid with a spatial resolution of 0.25° (27.75 km), while the JPL computing center's most recent version, RL06, has Mascon solutions that are defined on a grid with a spatial resolution of 0.5° (~55 km). Each GRACE ΔTWS for a given month displays the surface mass divergence from the baseline temporal average for that month (Wiese et al., 2019).

The reported GRACE anomalies in these mascon solutions are relative to a January 2004 to December 2009 mean baseline. The baseline can be changed depending on the requirements of the application (Landerer and Cooley, 2021). In this study GRACE TWS mean baseline was changed to 2008 – 2010 to match with in-situ groundwater data, because the majority of boreholes lack data from 2004 to 2009. This period was a lower-than-average rainfall period; therefore, a bias towards wet periods is expected, most results in TWS will be positive relative to this mean baseline. Furthermore, we could not use a post-2011 mean baseline because GRACE data started to have frequent gaps post-2011. Average monthly anomalies were estimated by subtracting the long-term average (2008 – 2010) from monthly values.

Due to the GRACE satellites' deteriorating batteries, there are noticeable gaps in the GRACE dataset as battery management began in 2011. These gaps endure for 4–5 weeks and happen every 5–6 months on average (Landerer and Cooley, 2021). Linear interpolation was used to fill in the monthly gaps (Rodell et al., 2018; Solander et al., 2017). The dataset also has a gap between the decommissioning of GRACE (October 2017) and the launch of GRACE-FO (May 2018). In our study we ran our analysis from 2008 to 2017 to better align with available in-situ groundwater data. As a result, the gap between GRACE and GRACE-FO was not filled.

3.2. Global Land Data Assimilation System (GLDAS)

Within the GLDAS initiative (Rodell et al., 2004), three land-surface models e.g., Catchment land surface model (CLSM) (Koster et al., 2000), NOAH (Niu et al., 2011) and VIC (Liang et al., 1994) are run offline from atmospheric models over the period from 1948 to 'today' (near real-time) at spatial resolutions ranging from 1 to 0.25°, using multiple state-of-the-art remote sensing and ground-based forcing datasets. Each model simulates soil moisture at different soil layers. Additionally, CLSM simulates daily shallow GWS at 0.25° spatial resolution. More information about GLDAS can be found in the Appendix Section A3 (Rodell et al., 2004).

3.3. GRACE-based groundwater storage

We estimate ΔGWS by deducting monthly anomalies of hydrologic water storage elements including reservoir storage and soil moisture from GRACE ΔTWS (Famiglietti et al., 2011; Landerer and Cooley, 2021; Masindi, 2021; Ramjeawon et al., 2022). The effect of snow water equivalent and biomass to terrestrial water storage is assumed to be negligible because Western Cape experiences a generally warmer climate (<0 °C to >36 °C (WCDoA, 2022)) and it is at a relatively low altitude (0 to 2 325 masl, with an average of 581 masl (Ahiakwo et al., 2018)). Snow water equivalent (SWE) from GLDAS CLSM shows that SWE in the study area is less than 0.035 cm (Fig A4.1). Biomass variations are not included because they have proven to be significantly less than the detection limit of GRACE (Rodell et al., 2005).

To deduct changes in soil moisture (ΔSM) from the GRACE ΔTWS data products we used root zone (RZ) soil moisture and soil moisture content from GLDAS LSMs (Table 2). See Rui et al. (2021) for more information about Soil moisture content and RZ soil moisture.

Surface water anomaly (ΔSW) deducted from GRACE ΔTWS in this research is the water from 44 dams/reservoirs distributed across the Western Cape (Fig. 4). The DWS provided weekly reservoir storage data in Million liters from 2000 to 2021. Full storage capacity of the Western Cape dams is 1865.7 Mm^3 (Western Cape Government, 2022). The WCWSS collective capacity is approximately 900 Mm^3, with six major dams contributing more to this capacity, while the eight minor dams only contribute 0.4% of the total capacity (Water stories, 2022). The WCWSS dams are in the southwest side of the province, while other dams are also not evenly distributed across the province, which biases surface water storage to certain areas. The GRACE-based monthly ΔGWS was estimated by subtracting the monthly ΔSM and ΔSW from the GRACE monthly ΔTWS (Eq. (1)). All parameters were converted to centimetres (cm to align with GRACE.

$$\Delta GWS = \Delta TWS - (\Delta SM + \Delta SW) \tag{1}$$

where Δ refers to the change over time with respect to base period (i.e., anomalies); GWS = Groundwater Storage; TWS = Terrestrial Water Storage; SM = Soil Moisture and SW = Surface Water.

3.4. GLDAS-based groundwater storage

Shallow unconfined aquifer's (<30 m) GWS is one of parameters calculated by GLDAS CLSM (Kruy and Ruangrassamee, 2022). The daily GWS from GLDAS-2.2 is accessible for unconfined aquifers from 2003 to the present (Kruy and Ruangrassamee, 2022; Li et al., 2020a, 2019a). The daily GWS used in this study was taken from the GLDAS-2.2 dataset from 2003 to 2020, with a spatial resolution of 0.25°. The GWS is calculated as a water column with a unit of "millimetre (mm)". Monthly GWS anomaly is calculated from Eq. (2):

$$\Delta \mathrm{GWS}_{\mathrm{M,GLDAS}} = \mathrm{GWS}_{\mathrm{M}} - \overline{\mathrm{GWS}_{2008\rightarrow2010}} \tag{2}$$

where $\Delta GWS_{M,GLDAS}$ is the change in GLDAS groundwater storage with respect to the 2008 to 2010 mean baseline for month M, GWS_M is the groundwater storage for month M, and $\overline{GWS_{2008\rightarrow2010}}$ is the average groundwater storage during 2008 - 2010. The parameters mentioned in Eq. (2) above are expressed in centimetres.

Table 2
Soil moisture datasets used.

LSM	Depth (cm)	Spatial resolution	Source
CLSM	100	0.25° x 0.25°	(Li et al., 2020a)
	100	1° x 1°	(Li et al., 2020b; Rodell et al., 2004)
NOAH	> 100	0.25° x 0.25°	(Beaudoing and Rodell, 2020a; Rodell et al., 2004)
	200	1° x 1°	(Beaudoing and Rodell, 2020b; Rodell et al., 2004)
VIC	> 10	1° x 1°	(Beaudoing and Rodell, 2020c; Rodell et al., 2004)

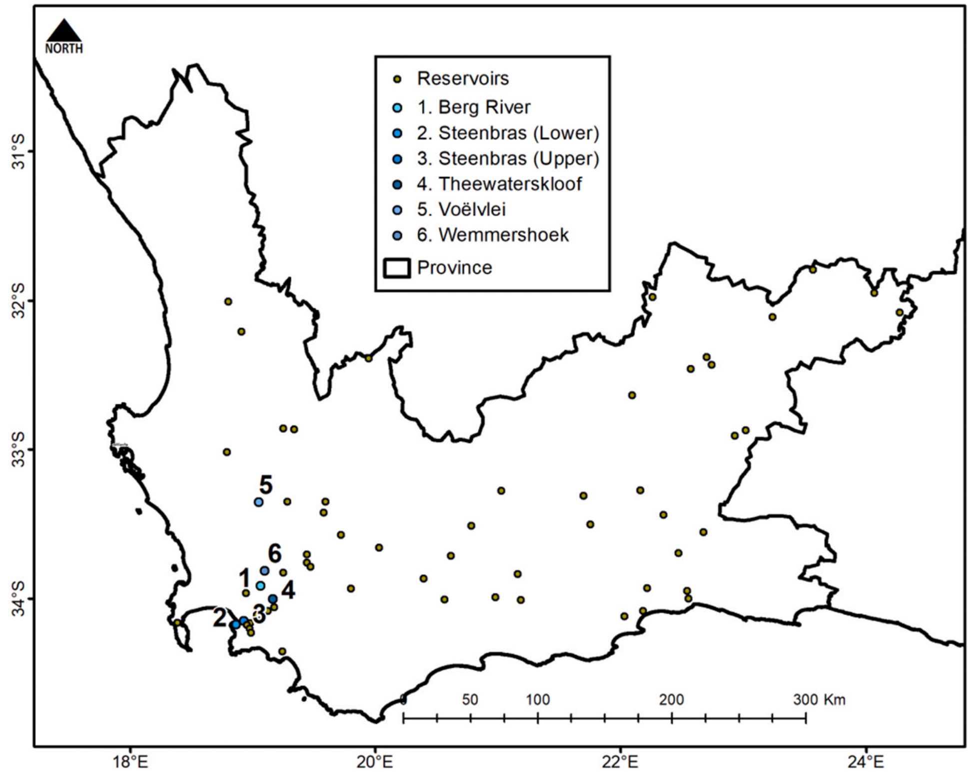

Fig. 4. Distribution of Western Cape reservoirs. The labelled dams are the six largest dams which make up the WCWSS.

3.5. *In-situ groundwater monitoring data*

Groundwater levels, and information about well casing and borehole lithologies were collected from National Groundwater Archive (NGA) of DWS. In-situ data available had frequent gaps and subsequently 166 boreholes distributed over 12 aquifers were selected based on the length and quality of the data record out of 938 boreholes available (Fig. 5 and Table 3). Gaps of up to three months were filled by linear interpolation. However, there was no metadata available to determine the aquifer type (unconfined, semi-confined, or confined) or storativity at each borehole. As a result, aquifer type, transmissivity, and storativity information were obtained from the literature. From this, TMG Aquifer was divided into two units namely the Upper and Lower Aquifer Units (UAU and LAU), which are unconfined and confined, respectively. Additionally, the Langebaan Road Aquifer was also divided into the UAU and LAU based on hydraulic head response (Israel et al., 2021; Vermaak, 2021). As part of the analysis, hydraulic head anomalies from boreholes screened in the same aquifer were averaged.

To compare GRACE derived data (ΔTWS/ΔGWS) with in-situ observations, it is essential to convert monthly groundwater hydraulic head anomalies into monthly ΔGWS as per Eqs. (3) and (4) (Bhanja et al., 2018; Hachborn et al., 2017; Nanteza et al., 2016; Swenson et al., 2006).

$$\Delta GWS_{OBS,confined} = S\Delta h \tag{3}$$

$$\Delta GWS_{OBS,unconfined} = S_y\Delta h \tag{4}$$

where S is the storativity (dimensionless), S_y is specific yield (dimensionless), and Δh are the changes in hydraulic head observed in-situ (cm). In our study, the value of storativity ranged from 0.001 to 0.0031 for confined and semi-confined aquifers, while specific yield ranged from 0.01 to 0.17 for unconfined aquifers (Campbell et al., 1992; Dennis and Dennis, 2012; Jovanovic et al., 2017; Rose, 2017; Rosewarne, 2002, 1981; Timmerman, 1985).

3.6. *Statistical analysis*

The Pearson correlation coefficient (r), a measure of linear relation between two variables, was used to compare in-situ ΔGWS with ΔTWS, GRACE-based ΔGWS, and GLDAS-based ΔGWS.

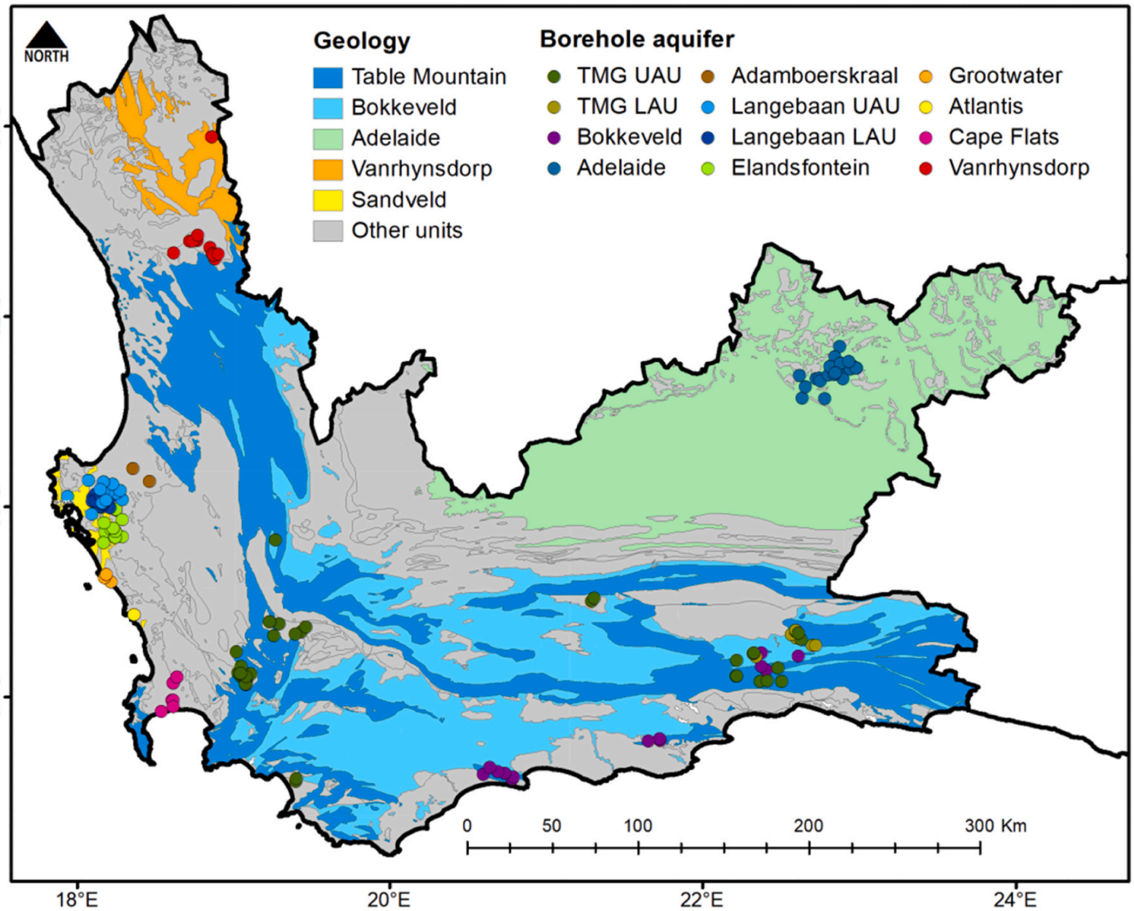

Fig. 5. Regional geologic map including borehole sites across Western Cape.

Table 3
Aquifers in the Western Cape with sufficient in-situ groundwater data.

Aquifer Type	Aquifer unit		Area (km^2)	No. of boreholes
Intergranular	Adamboerskraal		NA	2
	Atlantis		130	2
	Cape Flats		630	8
	Elandsfontein		NA	14
	Grootwater Primary		65	3
	Langebaan Road	UAU	NA	15
		LAU		18
Fractured	Adelaide		194,000	28
	Bokkeveld		28,000	15
	Table Mountain Group	UAU	37,000	39
		LAU		9
Karst	Vanrhynsdorp		4 000	13

4. Results

4.1. Grace ΔTWS

GRACE ΔTWS data from two products were obtained from 2003–2020 (Fig. 6) and compared with monthly rainfall averaged from 258 weather stations in the Western Cape. Fig. 6 shows marked seasonality, where dry (December to March) and rainy (July to November) periods are clearly distinct. Noticeable reductions in TWS coincide with recent droughts in the Western Cape, indicated in Fig. 6. It is possible to identify a few differences between the two GRACE products: CSR shows a greater range of ΔTWS within seasons compared to the JPL; however, when the interannual variability is examined, both show similar patterns.

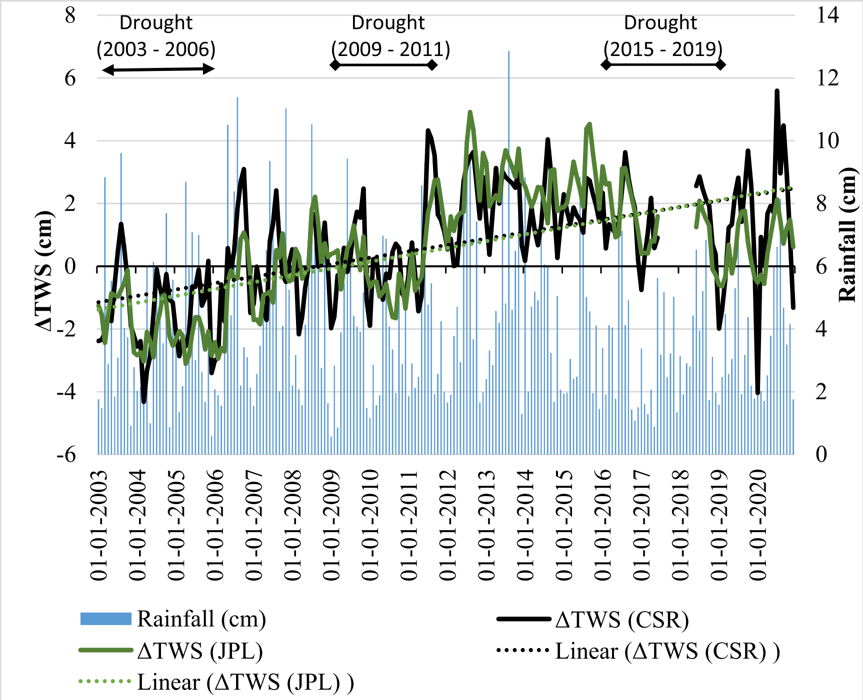

Fig. 6. Time-series of terrestrial water storage anomalies (ΔTWS) from the two GRACE products and monthly rainfall averaged from 258 weather stations in the Western Cape. The anomalies correspond to spatial averages of TWS relative to the 2008–2010 mean baseline. The gap between June 2017 and June 2018 is because GRACE was recommenced from June 2018 with GRACE-FO.

4.2. Combined GLDAS and GRACE-based estimates of ΔGWS

GLDAS land surface models (CLSM, NOAH and VIC) and surface water data were obtained from 2003 to 2020 (Fig. 7). Results revealed that ΔSM was highly seasonal, where the dry (January to March) and wet (July to September) seasons can be clearly distinguished. The CLSM displayed a smaller ΔSM amplitude compared to NOAH and VIC models. Also, ΔSW ranges were less comparable to ΔSM from NOAH and VIC.

Land surface models and ΔSW were combined with GRACE ΔTWS data across the same period to obtain and estimate of ΔGWS (Figs. 8 and 9). Between the two GRACE products, the ΔGWS from CSR (Fig. 8) has greater amplitudes than the product from JPL (Fig. 9). Furthermore, estimated ΔGWS from both JPL and CSR, in combination with ΔSM from GLDAS CLSM (both spatial resolutions, where 0.25 is 0.25° and 1 is 1°), had smaller amplitudes compared to other combinations.

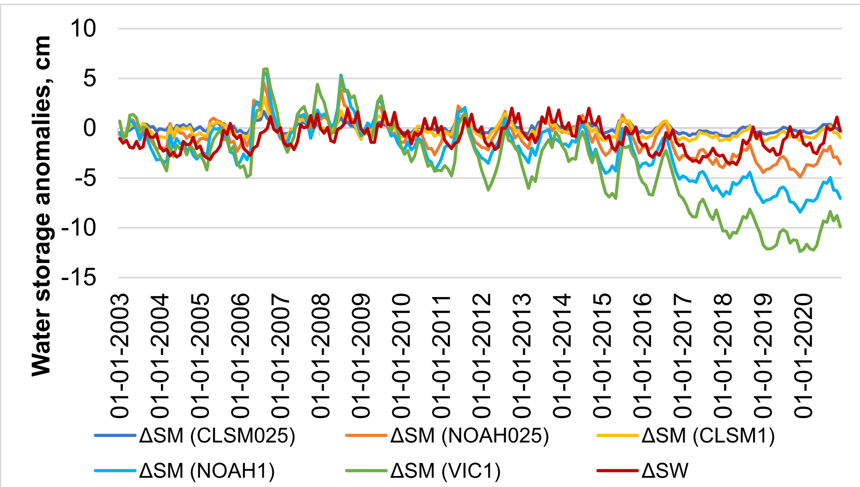

Fig. 7. Land surface models (CLSM, NOAH and VIC at 0.25° and 1° spatial resolution) and surface water data anomalies.

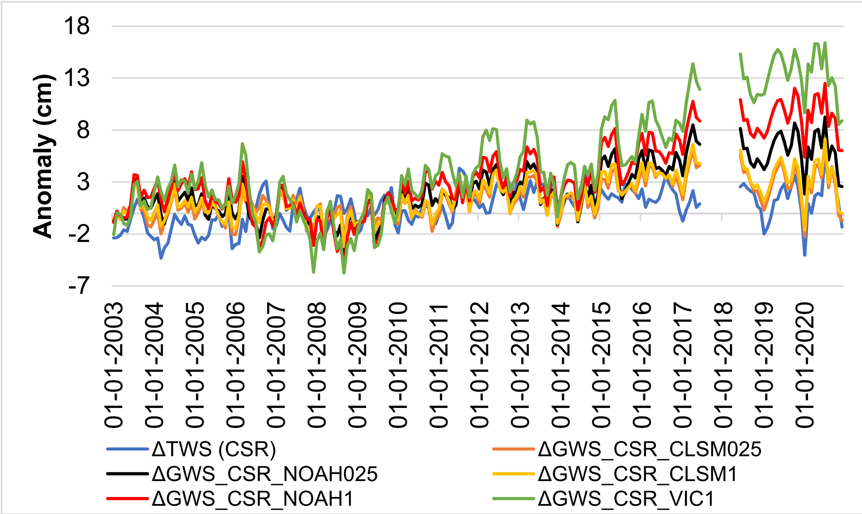

Fig. 8. Estimated ΔGWS and measured TWS anomalies: CSR (2003 to 2020). The gap is due to GRACE satellites gap between 2017 and 2018.

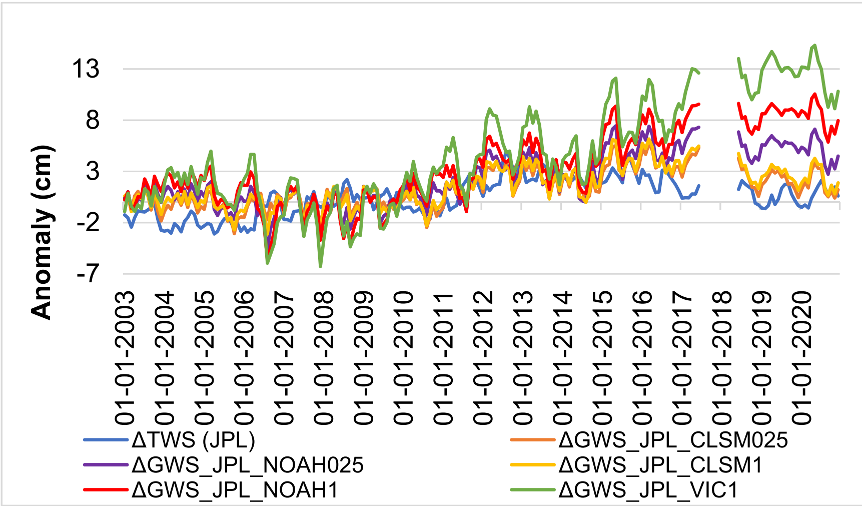

Fig. 9. Estimated ΔGWS and measured TWS anomalies: JPL (2003 to 2020). The gap is due to GRACE satellites gap between 2017 and 2018.

4.3. GLDAS-based estimates of ΔGWS

Changes in GWS from GLDAS show strong seasonality, where dry (March) and rainy (September) periods are clearly distinct from 2003 to 2020 (Fig. 10). In addition, reductions in shallow GWS that coincide with periods of severe drought in the Western Cape (2015–2018) are also visible.

4.4. Comparison of results and statistical analysis

Comparisons were performed between (1) ΔTWS, GRACE-based ΔGWS, and GLDAS-based ΔGWS data and (2) ΔGWS from in-situ data. The results are presented in terms of Pearson r-values. Table 4 and Fig. 11 represent the results of the highest Pearson correlation *r*-values out of 300 correlation tests done at monthly time-steps for corresponding data periods of the in-situ ΔGWS with ΔTWS (JPL), GRACE-based ΔGWS with soil moisture (CLSM), and GLDAS-based ΔGWS. Table A5.1 shows the full results. Correlation is significant at the 0.01 level (2-tailed).

Table 4 shows that correlation between ΔTWS from JPL and in-situ ΔGWS data are greatest for the Adelaide Subgroup ($r = 0.69$) and Bokkeveld Aquifers ($r = 0.58$). GRACE-based ΔGWS data with soil moisture from CLSM had the greatest correlation ($r = 0.52$) with Bokkeveld Aquifer in-situ ΔGWS. GLDAS-based ΔGWS data had the highest *r*-value with ΔGWS from the unconfined Table Mountain Group (TMG) Aquifer ($r = 0.83$) and Cape Flats Aquifer ($r = 0.73$).

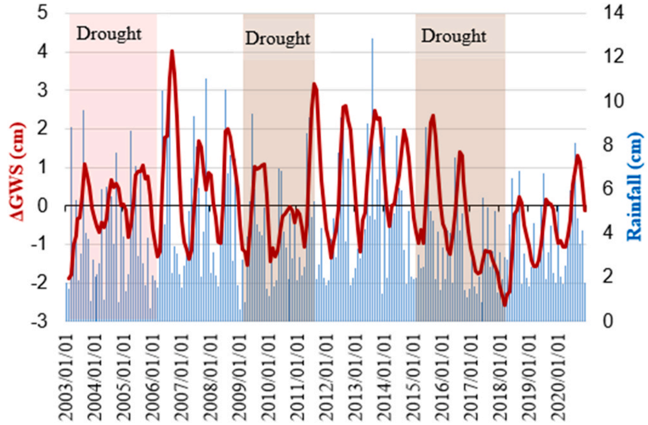

Fig. 10. Time-series of GLDAS shallow groundwater storage variations and monthly rainfall values averaged from 258 weather stations in the Western Cape.

5. Discussion

The Western Cape is comprised of three different climatic zones that experience extreme rainfall events at different times, which ultimately affect GRACE ΔTWS and ΔGWS data. Unconfined aquifers such as the Adelaide Subgroup, Cape Flats Aquifer and TMG UAU tend to have high transmissivities and a quick response to heavy rainfall events, and are more likely to be consistent with GRACE data products, leading to strong positive correlation (Neves et al., 2020).

The highest positive correlation ($r = 0.69$) was between ΔTWS and in-situ ΔGWS for the Adelaide Subgroup Aquifer (Table 4 and Fig. 11a). This positive correlation may be due to the large areal extent of the Adelaide Subgroup Aquifer compared to other aquifers in the Western Cape (Table 1 and Fig. 5). The areal extent of the Adelaide Subgroup Aquifer is 194,000 km^2, which is close to the GRACE recommended resolution of 200 000 km^2. The Adelaide Subgroup Aquifer is part of the Karoo Supergroup (Richey et al., 2015; Scanlon et al., 2022), the largest aquifer in South Africa (Woodford and Chevallier, 2002). The high correlation may also be due to the unconfined nature of this aquifer, with most boreholes (16 of 28) being cased $<$ 30 m deep and because the aquifer is in the Nama Karoo biome where the estimated potential reductions in groundwater recharge are small compared to the Fynbos biome (dominant biome in the study area, appendix A6) when invaded by alien plants (van Wilgen et al., 2008).

Moreover, the positive correlation between GRACE ΔTWS and GWS of the Adelaide Subgroup Aquifer may be due to the aquifer's large fluctuations in mass changes (Fig. 11a) relative to the other aquifers in the Western Cape. If there are very large mass changes due to dewatering of the aquifer, GRACE may be able to detect storage changes, despite it being a small area compared to the GRACE spatial resolution (Long et al., 2016). The Beaufort West municipality located within this aquifer uses groundwater extraction extensively to supply the water needs of the community (Ligavha-Mbelengwa and Gomo, 2020), with approximately 1.9 Mm^3 per annum abstracted from the Beaufort West well fields (Rose, 2017).

The decline in groundwater storage from March 2008 to December 2010 (Fig. 11a) was due to an increase in groundwater use during the 2009 to 2011 drought (Visser, 2021). Groundwater levels in the Beaufort West town's significant North End Aquifer, which is typically known for its quick recharge capability, decreased from 13 m to 36 m below ground level between November 2008 and December 2010 (Visser, 2021). In 2011 Beaufort West built a wastewater treatment plant, residents started to use treated wastewater and reduced groundwater use (Visser, 2021) and also received the anomalously wet years in 2011–2013, hence a large increasing trend in groundwater storage from 2011 to 2013 (Fig. 11a). From 2014 to 2016 there was less than average rainfalls, which drove the local population to increasingly depend on borehole water, and water from the wastewater treatment plant. The town again was hit by a major drought from 2017 to 2019, during this time there was less water from the wastewater treatment plant and in August 2018 a sewage pipe broke which stopped wastewater from going into the plant (Visser, 2021). As a result, groundwater storage continued to decline from May 2016 to November 2018. Fortunately, average rates of rainfall returned in May 2019 leading to a recovering trend in groundwater storage from 2019 onwards (Fig. A1.1d).

The ΔTWS that corresponds better with the Adelaide Subgroup Aquifer were from JPL, even though JPL has a lower spatial resolution compared to CSR. This may be because a scaling/gain-factor (a technique to improve spatial resolution) was applied to the dataset in accordance with guidelines for hydrological studies (Ramjeawon et al., 2022; Wiese et al., 2019).

There was a positive moderate correlation ($r = 0.58$) between ΔTWS (JPL) and ΔGWS of the Bokkeveld Aquifer (Fig. 11b). This correlation may be as a result of the Coastal Resolution Improvement (CRI) filter applied to the JPL dataset, which cuts down on signal leakage losses along coastlines (Wiese et al., 2019). Both Adelaide Subgroup and Bokkeveld Aquifers align very well with JPL ΔTWS time-series during the 2009 to 2011 drought. The regions where these two aquifers are situated (Central Karoo and Garden Route District) were the most affected by this drought in the Western Cape (Fig. A7.1; Holloway et al., 2012; Visser, 2021). Within the analysis period, large mass change (negative change) was observed during the 2009 to 2011 drought. After 2011, the Adelaide Subgroup and Bokkeveld Aquifer were less aligned with GRACE ΔTWS, which may be the result of linear interpolation between

Table 4
Correlation coefficient (r) between GRACE-based GWS/TWS anomalies, GLDAS-based GWS anomalies and in-situ GWS anomalies. Correlation is significant at the 0.01 level (2-tailed). Where p = p – value. Values in brackets are sample size, r is based on. SM represent average ΔSM, and 1 = 1° and 025 = 0.25° spatial resolution.

		ΔGWS_JPL_CLSM025	**ΔGWS_CSR_VIC1**	**ΔGWS_JPL_NOAH1**	**ΔGWS_JPL_VIC1**	**ΔGWS_JPL_SM1**	**ΔTWS (JPL-M)**	**ΔGWS (GLDAS)**
TMG UAU	**r**	-.45	-.53	-.52	-.56	-.55	.29	.83 (114)
	p	< .001	< .001	< .001	< .001	< .001	.00	<.001
Bokkeveld	**r**	.52 (114)	.31	.44	.39	.44	.58 (114)	.09
	p	<.001	<.001	<.001	<.001	<.001	<.001	.35
Adelaide	**r**	.34	.17	.23	.24	.26	.69 (114)	.36
	p	<.001	.07	.01	.01	.01	<.001	<.001
Cape Flats	**r**	-.35	-.47	-.46	-.50	-.48	.24	.73 (102)
	p	< .001	< .001	< .001	< .001	< .001	.02	<.001

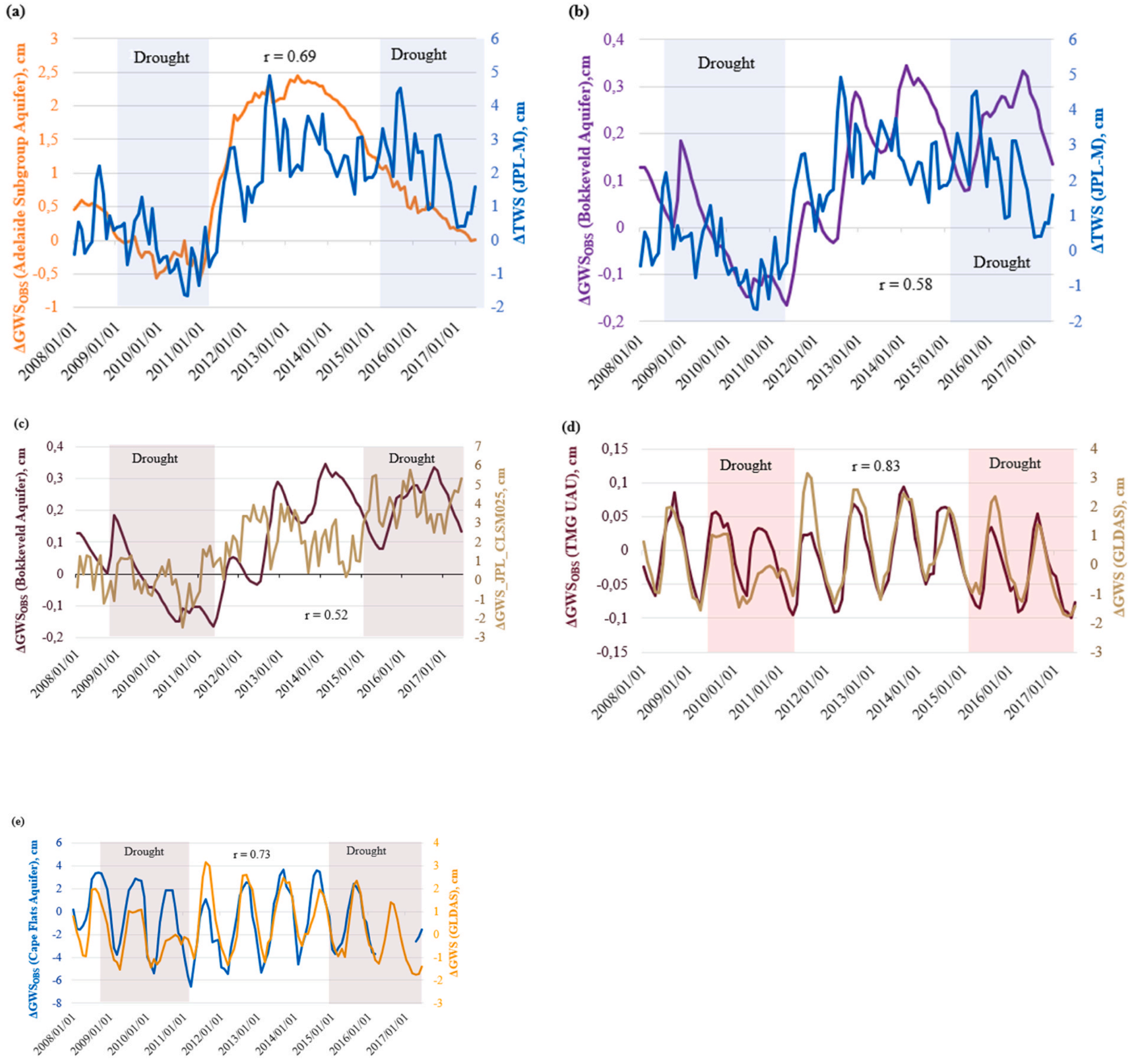

Fig. 11. Monthly anomaly GWS_{OBS} data from the National Groundwater Archive compared with ΔTWS (a-b), GRACE-based ΔGWS estimates using CLSM soil moisture data (c), and GLDAS-based ΔGWS (d-**e)**.

measurements.

Moderate correlation between GRACE ΔGWS and Bokkeveld Aquifer may be because Bokkeveld Aquifer has a positive correspondence with the Adelaide Subgroup Aquifer (Table A8.1), which has high correspondence with ΔTWS. However, poor correlation between GRACE-based ΔGWS and Adelaide Subgroup Aquifer may be due to sparsely distributed reservoirs and suggested less soil moisture overlaying the Adelaide Subgroup Aquifer (Fig. 4). GRACE-based ΔGWS might be biased against Adelaide Subgroup Aquifer, alternatively there might be less ΔSM and ΔSW bias in the Bokkeveld Aquifer, hence the good correspondence with GRACE-based ΔGWS. Good correspondence between ΔGWS of the Bokkeveld Aquifer and GRACE-based ΔGWS estimated from a combination of ΔSM from CLSM, may be soil moisture has little representativeness in the ΔTWS of the area (Melati et al., 2019), indicated by small CLSM amplitudes (Fig. 7). Results from the NOAH and VIC models were unsatisfactory as in semi-arid areas in Brazil (Melati et al., 2019). Ranges from VIC and NOAH were significantly greater than those from CLSM (Figs. 7, 8 and 9). These variations can be related to parameterizations of the GLDAS LSMs; however, the lack of in-situ soil moisture observations in the Western Cape makes it difficult to improve the models when assimilating data. The considerable variations among GLDAS land surface models have already been confirmed in related studies (Feng et al., 2013). GLDAS CLSM uses GRACE data to estimate TWS and thus, one can calculate GWS by subtracting soil moisture from TWS; however, the other two models (NOAH and VIC) only estimate soil moisture (and not GWS).

Table Mountain Group UAU had a strong positive correlation of 0.83 with GLDAS GWS (Fig. 11d), while Cape Flats Aquifer also had a strong positive correlation of 0.73 with GLDAS GWS (Fig. 11e). The strong positive correlations may be due to the ability of GLDAS

CLSM to simulate unconfined/shallow GWS driven by land-atmosphere interaction only, not groundwater withdrawals or ΔGWS in deep aquifers (confined), which are all included in the GRACE data (Li et al., 2019). Therefore, the TMG UAU and Cape Flats Aquifers may correspond well with GLDAS because they are unconfined aquifers and respond quickly to precipitation.

Some characteristics explain the low performance of a few aquifers in terms of ΔTWS and GRACE-based ΔGWS data. In this study, a GRACE pixel can consist of both unconfined (Adelaide Subgroup Aquifer, TMG UAU and Cape Flats Aquifer) and confined aquifers (e.g., Adamboerskraal, TMG LAU and Grootwater Aquifer), due to coarse spatial resolution, making our study area a complex hydrological environment, as it consists of multiple aquifer systems. GRACE ΔTWS are best when compared with unconfined groundwater observations (Brookfield et al., 2018; Rodell, 2022). A recent paper characterized the performance of GRACE in different aquifer systems, and also sought to identify the applicability of GRACE data (Katpatal et al., 2018). Their results showed high correlation coefficients for simple aquifers, and smaller values in regions with multiple aquifer systems. Some aquifers recover rapidly post droughts (Adelaide Subgroup Aquifer and TMG UAU) while some do not (Vanrhynsdorp Aquifer) (Fig A1.1), reducing ΔTWS performance in the Western Cape. For regions with an area greater than 200 000 km^2, the GRACE's coarse spatial resolution is preferable (Guo et al., 2022), of which only Adelaide Subgroup Aquifer has areal extent closer to this spatial resolution. Both Huang et al. (2016) and Scanlon et al. (2012) pointed out the difficulties in connecting GRACE-based estimates of ΔGWS to point-scale in situ ground observations or to regions smaller than the GRACE footprint. Additionally, aquifers not having large mass changes due to pumping reduces GRACE performance.

6. Conclusions

GRACE and GLDAS data offer a chance to identify the spatial and temporal ΔGWS over broad catchment areas, even in places that lack adequate groundwater monitoring networks. The lack of representative aquifer storage parameter values such as storativity and specific yield, lack of sufficient groundwater monitoring boreholess and inconsistent and erratic groundwater observation data in the Western Cape prompted the application of the GRACE satellite product and GLDAS to determine ΔTWS and ΔGWS over a large region and provided the opportunity to understand how GRACE and GLDAS data can be used as a monitoring tool for groundwater reserves in the Western Cape.

The GRACE satellite data for the Western Cape was successfully processed and analyzed to determine the ΔGWS by removing the ΔSM and ΔSW from the ΔTWS. The GRACE-based ΔGWS and the ΔTWS and GLDAS-based ΔGWS were validated using limited in-situ groundwater level data measured from piezometers located in the Adelaide Subgroup, Bokkeveld, Table Mountain Group, Vanhynsdorp and Sandveld (Adamboerskraal, Langebaan Road, Elandsfontein, Grootwater, Atlantis and Cape Flats) aquifers. The GRACE-based ΔGWS and ΔTWS for the period from 2008 to 2017 indicated that ΔTWS from JPL was suitable to represent ΔGWS_{OBS} for the Adelaide Subgroup Aquifer ($r = 0.69$) and ΔGWS from JPL and CLSM (ΔSM) combination was suitable to represent ΔGWS_{OBS} for the Bokkeveld Aquifer ($r = 0.52$). GLDAS-based ΔGWS was suitable to represent ΔGWS_{OBS} for the unconfined Table Mountain Group ($r = 0.83$) and Cape Flats ($r = 0.73$) Aquifers.

This study shows that, in areas with a lack of data, utilizing a strategy that integrates a variety of techniques and uses remotely sensed and in-situ data is essential for enhancing understanding of groundwater resources at a provincial scale. The results showed that ΔTWS of an area smaller than GRACE footprint could be detected by the GRACE signal during drought periods. In addition, GLDAS CLSM can only capture GWS in shallow aquifers. Groundwater storage changes in the Western Cape may be identified and tracked using GLDAS GWS and GRACE TWS data. Since change in groundwater storage is minimal, groundwater can be used to help meet the province's future water needs and reduce the strain on surface water resources. However, concurrent management of surface water (mainly during above-average-rainfall periods) and GWS (mostly during droughts), and promotion of other technologies (e.g., managed aquifer recharge, desalination) where suitable should also be considered to ensure sustainable groundwater management.

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CRediT authorship contribution statement

Chow Reynold: Conceptualization, Formal analysis, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Brookfield Andrea:** Writing – review & editing. **Münch Zahn:** Visualization, Writing – review & editing. **Nenweli Ritshidze:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **Watson Andrew:** Conceptualization, Formal analysis, Resources, Supervision, Visualization, Writing – review & editing, Writing – original draft.

Declaration of Competing 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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.101699.

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