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Research paper

Monitoring seasonal groundwater storage anomalies using remote sensing

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Knowledge of the dynamics of groundwater storage is essential in understanding its driving processes and for informed decision-making. This requires data with adequate precision, which can be obtained from in-situ observations and remote sensing products. While field-based methods are expensive to conduct in low-income countries, satellite products are relatively cheap and provide near real-time data to monitor groundwater resources. This study analyses the seasonal dynamics of groundwater storage anomalies in Zimbabwe. The study utilised the Gravity Recovery and Climate Experiment (GRACE) satellite groundwater monthly point data spanning January 2011 to July 2017. Ordinary kriging was performed to show the spatial variations of groundwater anomaly levels for individual months. Maps for the dry season from April to October were merged together as well as for the wet season from November to March. The final raster maps showed long-term average groundwater level anomalies for each season. Findings show significant variations in groundwater storage level anomalies within and between seasons. The general pattern is that groundwater storage levels increased from the south to north of Zimbabwe. During the wet and dry seasons of 2015, almost 75% of the country had an increase in groundwater storage. This rapid approach using satellite-derived groundwater data, in comparison to other optical remote sensing techniques, is useful for rapid groundwater assessment and management.

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INTRODUCTION

Groundwater is an important resource that can be used to meet water needs for the rising global population, including agricultural, industrial and recreation demand (Thomas et al., 2017). It accounts for nearly 30.1% of the world's freshwater supplies, contributes 42% of water used in agriculture, 30% of water for industry and 50% of water for domestic use (Agrawal et al., 2021). Nevertheless, groundwater levels are decreasing in many parts of the world as a result of global climate change and rising agricultural activities (Singh et al., 2023; Shen et al., 2015; Castle et al., 2014). It has become crucial to implement effective groundwater management strategies, especially in drylands, in order to achieve the Sustainable Development Goals (SDGs). For instance, SDG 6 (clean water and sanitation for all) and its major target 6.1 on safe and affordable drinking water. Sound management of groundwater resources reduces water scarcity, and ensures access to safe and clean drinking water (Jarvis, 2021). Thus, the scope of this work was to use observations from the Gravity Recovery and Climate Experiment (GRACE) satellite to monitor changes in groundwater storage in Zimbabwe, a water-scarce country.

Compared to surface water, groundwater is ubiquitous, more accessible, more reliable, less prone to pollution, requires relatively less capital cost and is less sensitive to climate change (Nhamo et al., 2020). Its low sensitivity to short-term and seasonal climatic variations makes it ideal for community adaptation to negative impacts of droughts on food production (Foroumandi et al., 2023; Chikodzi et al., 2014). Almost 70% of the population of Southern Africa relies on groundwater as its primary water source (Brauns et al., 2020; Nhamo et al., 2020; Thomas et al., 2017). It is more valuable in arid and semi-arid regions due to the scarcity of surface water resources (Chikodzi et al., 2014). It is also perceived as safer for various types of human consumption than surface water. Nevertheless, groundwater is a finite resource which is relatively difficult and expensive to identify, explore, quantify, monitor and exploit.

Regardless of groundwater being the largest readily available fresh-water resource in the world, knowledge of its storage has remained poor (Agrawal et al., 2021). The amount of groundwater storage is influenced by climate variables, local geology, topography, and land use and land cover changes (Verma and Katpatal, 2020; Katpatal et al., 2018; Chikodzi et al., 2014). Low-lying discharge sites exhibit substantially less change in groundwater decline than upland recharge sites (Chikodzi, 2013a). Upland areas are zones of groundwater recharge while valley bottoms are discharge sites. In order to systematically manage and prevent its depletion and mining, its storage changes needs to be routinely monitored using effective tools. In resource-poor arid and semi-arid regions in particular, exploitation of groundwater is a challenging task due to scarcity of resources. The density of monitoring networks is therefore very low. In some areas the networks are scarce, non-existent, costly, difficult to operate and labour intensive (Ansems, 2016). As a result, the data are usually of poor quality and unrepresentative, hence limiting their use in monitoring groundwater, hydrological model development, and calibrating and validating groundwater model parameters (Jyolsna et al., 2021).

Routine monitoring of groundwater storage fluctuations is an important activity in hydrology. It provides relevant information for many applications, including resource estimation, sustainable utilisation and exploitation strategies (Jyolsna et al., 2021; Kuhn et al., 2019; Chikodzi, 2013a). This involves gathering, collating and analysing the information to determine whether the water table is rising, falling or remains static (Shen et al., 2015). The sampling protocol requires a series of in-situ groundwater level measurements from boreholes and wells taken regularly over a long period to track the direction of storage changes, and identify recharge and discharge points (Muzenda et al., 2019). Ground-based data is limited in availability, due to poor spatial coverage of observation stations (Brauns et al., 2020; Bonsor et al., 2018). To overcome the problems of accessibility, including the costs of setting up well-equipped stations, and the limited spatial and temporal data coverage inherent in using in-situ measurements, the GRACE satellite products are often used for predicting groundwater storage at local, regional and global scales (Yin et al., 2022; Jyolsna et al., 2021). In addition, compared to other remote-sensing techniques, such as MODIS or Sentinel-1 (Ibrahim et al., 2024; Masood et al., 2022), GRACE provides unique advantages in measuring terrestrial water storage anomalies due to its ability to detect changes in the Earth's gravitational field (Adams et al., 2022; Yin et al., 2022; Verma and Katpatal, 2020).

Gravity recovery and climate experiment

GRACE is a joint mission of NASA and the German Aerospace Center, launched in 2002 to measure variations in the earths' gravity field, which shows changes in mass fluxes across the globe (Verma and Katpatal, 2020; Katpatal et al., 2018). Since 2002, GRACE and the follow-on mission, GRACE-FO, directly track changes in total water storage anomalies, which refer to equivalent water thickness anomalies. Total water storage anomaly (T) is estimated according to the following equation (Verma and Katpatal, 2020):

$$T = C + S + N + M + G \quad (1)$$

where: C is canopy water storage anomaly, S is the surface water anomaly, M is the soil moisture anomaly, N is the snow water equivalent anomaly, and G is the groundwater storage anomaly. Changes in total water storage anomaly indicate whether a region is gaining or losing water. Hydrologic data are presented as anomalies because GRACE does not directly observe the gravitational pull of water. The anomalies represent the difference between a given month's observation and a multi-year mean. From gravity anomalies, groundwater storage is detected as the terrestrial water storage anomaly, a measure of vertically integrated water storage change from land surface to the deepest aquifer (Ali et al., 2022; Verma and Katpatal, 2020).

Comparable studies on seasonal fluctuations of groundwater levels using satellite remote sensing in Zimbabwe are lacking. The work by Chikodzi (2013a) only focused on annual groundwater storage changes. However, such as large temporal scale tends to mask details relevant to water resource planning. This study determines the spatial and temporal variations of groundwater storage levels using remotely sensed GRACE satellite data. No effort was made to validate GRACE satellite data because previous studies have already done so using well and borehole observations with acceptable results (Verma and Katpatal, 2020; Katpatal et al., 2018). Strong and significant correlations between groundwater storage levels from GRACE data and in-situ measurement were observed in the humid tropics and monsoon climates of India, China and Bangladesh (Satish-Kumar et al., 2023; Yin et al., 2022; Verma and Katpatal, 2020), semi-arid regions of Australia (Zhao et al., 2017) and in Niger and the central United States (Strassberg et al., 2009).

MATERIALS AND METHODS

Description of study area

Zimbabwe (Fig. 1) is a landlocked country in Southern Africa covering an area of 390 760 km^2 and has a population of 15 178 979 people (ZimStat, 2023).

The country is bordered by Zambia in the north, South Africa in the south, Mozambique in the east and Botswana to the west. Elevation data used in Fig. 1 were from DivaGIS Shuttle Radar Topographic Mission (SRTM), which has a 30 m spatial

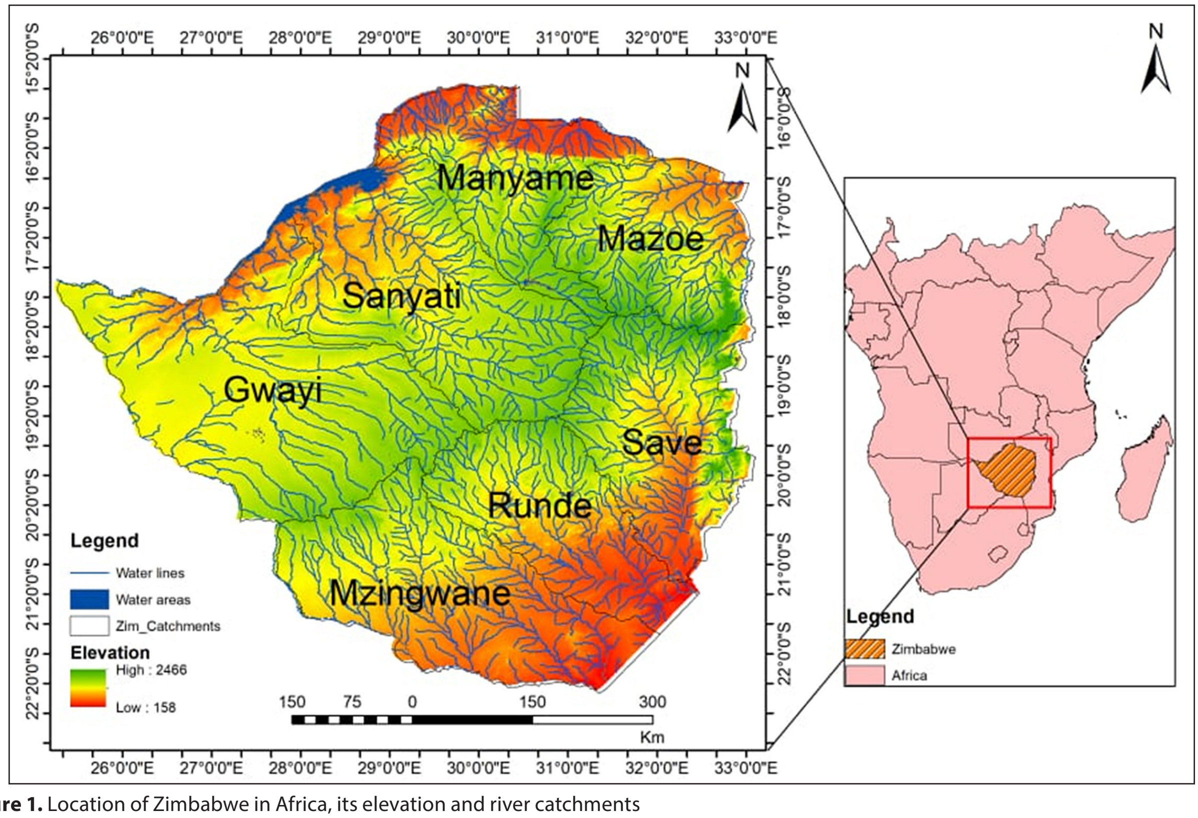

Figure 1. Location of Zimbabwe in Africa, its elevation and river catchments

resolution. Water lines were later derived from this elevation data through DEM hydro-processing in ILWIS. These two datasets are some of the key non-climatic variables that control groundwater potential in an area. Zimbabwe is a semi-arid country that receives an average annual rainfall of 657 mm (FAO, 2000). Generally, rainfall decreases from north to south and east to west in response to the direction of moisture-bearing winds from the ocean, and the influence of mountain and water bodies. Areas occupied by reservoirs, mountains, plateaux and cities also receive higher rainfall than the surrounding countryside. The rainfall season, which extends from November to March, is characterised by mid-season droughts. Around 80% of the population is concentrated in areas where rainfall is unreliable and access to water for productive use is limited. Annual rainfall ranges from 1 000$^+$ mm/year in the Eastern Highlands to around 300–450 mm/year in the low-lying areas to the extreme north and south of the country (Mazvimavi, 2003). Only 37% of the country receives rainfall adequate for crop production (Manatsa et al., 2011).

Almost 70% of the country is covered by Precambrian basement and metavolcanic aquifers, which comprise vast areas of gneissose rocks into which younger granite bodies of various sizes have been intruded (Bonsor et al., 2018). These basement aquifers have low groundwater yield as compared to moderate yield volcanic aquifers in the southern part of the country (Oesterlen and Lepper, 2005; Sibanda et al., 2009). In the north west, there are unconsolidated sediment aquifers with high groundwater yield. A few parts of the country have fractured meta-sedimentary aquifers with moderate to high groundwater yield (Fig. 2). Most aquifers are unconfined, shallow, and formed by crystalline rocks. This explains the quick response of groundwater to precipitation recharge (Chikodzi, 2013a).

Many dry areas of Southern Africa depend on groundwater for rural and urban water supply because it responds more slowly to meteorological conditions than surface water (FAO, 2000). In Zimbabwe, groundwater is abstracted mainly for mining, agriculture and potable water supply (Muzenda et al., 2019). Large-scale borehole drilling is being promoted to mitigate against the effects of droughts. FAO (2000) estimated that the total amount of renewable water resources available in the country is 20 billion m^3 per year. This comprises 11.26 billion m^3 of surface water and 6 billion m^3 of groundwater produced internally and 7.74 billion m^3 of water entering the country. Groundwater from boreholes and wells provides potable water to about 38% of the country's 3 818 992 households (Nhamo et al., 2020). Approximately 70% of Zimbabwe's rural population depends on groundwater for domestic use, animal watering and irrigation (Jarvis, 2021; Nhamo et al., 2020). Groundwater abstraction from 40 000 rural boreholes is about 35 million m^3 annually (Edokpayi et al., 2018). In urban areas the government and private sector, due to poor rainfall and increasing urbanisation (Mazvimavi, 2003), are also funding drilling of boreholes. Groundwater depletion has significant socio-economic impacts, particularly in rural areas. For instance, in the drought-prone regions, reduced groundwater levels have led to decreased agricultural productivity, exacerbating food insecurity (Mazvimavi, 2003).

Data sources and processing

Figure 3 shows the approach that was adopted in this study.

Geo-referenced global GRACE satellite data, were downloaded from the NASA website (http://www.csr.utexas.edu/grace/gravity/; http://podaac.jpl.nasa.gov/grace/) with a spatial resolution of 1° x 1°.

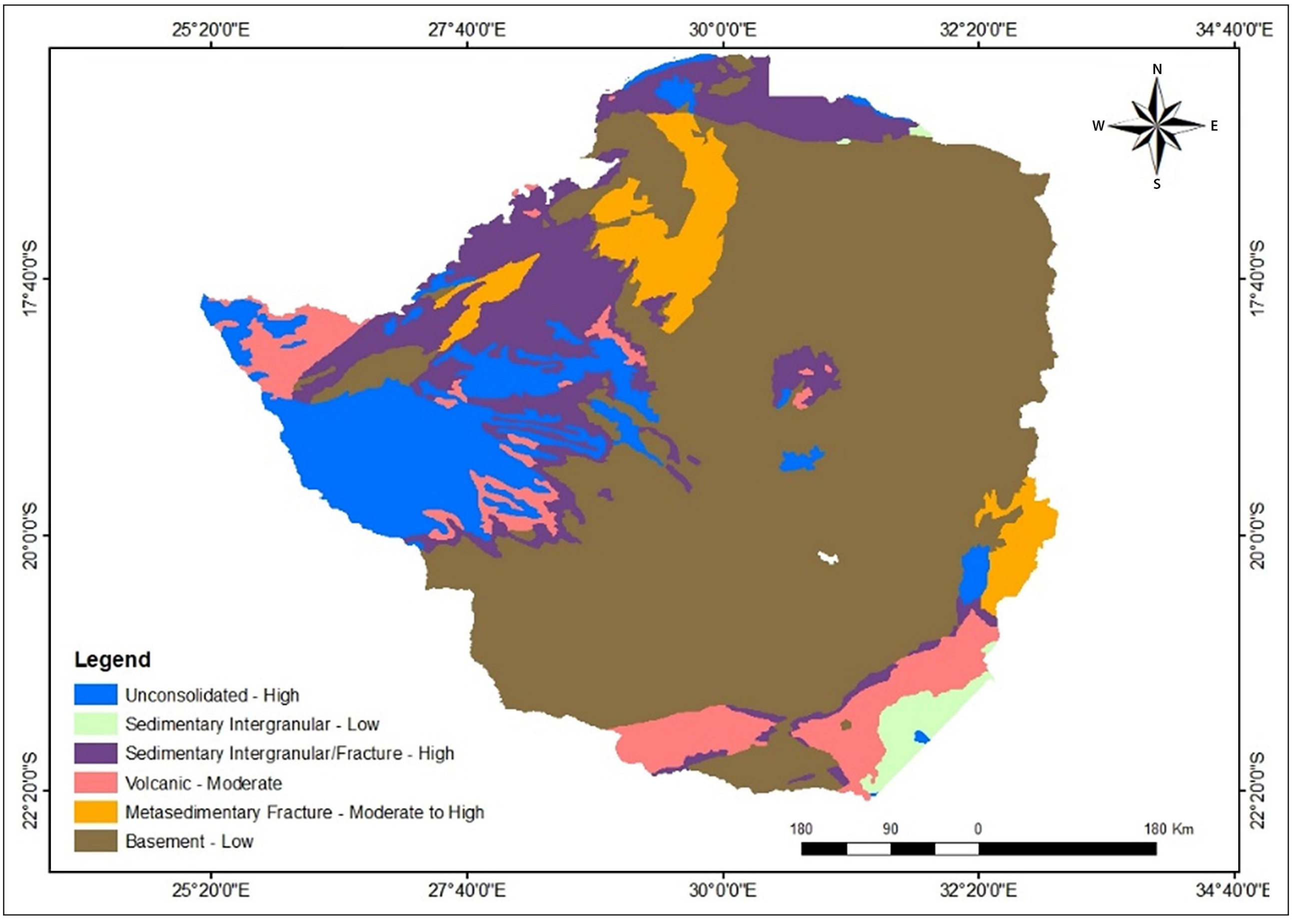

Figure 2. Aquifer types and groundwater potential in Zimbabwe, dominated by basement aquifers of low groundwater yield (Source: MediaWiki, 2024)

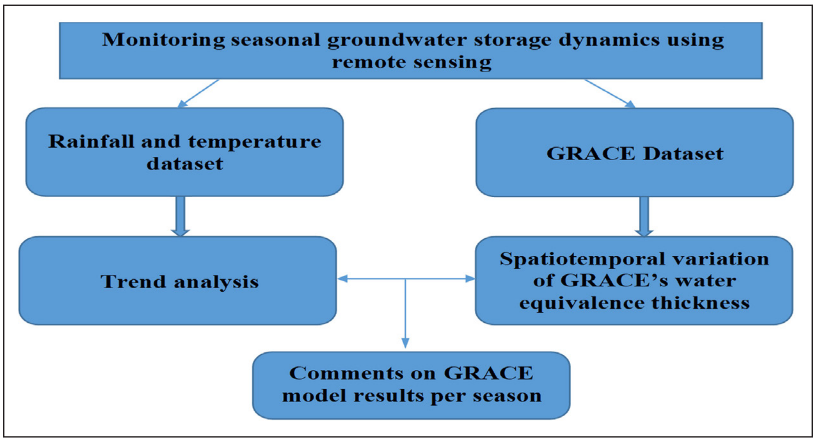

Figure 3. Methodological approach followed in this study

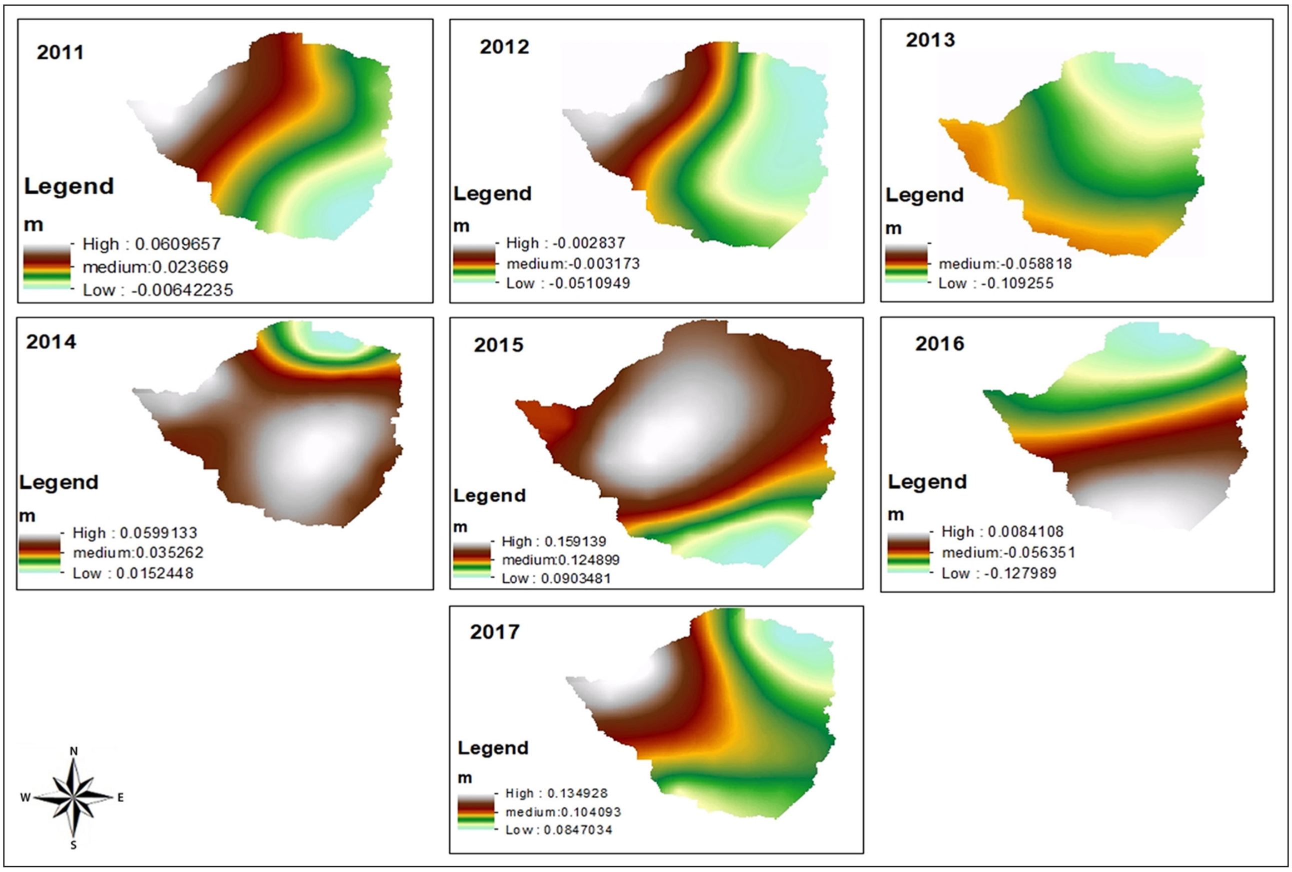

Figure 4. Variations of wet season groundwater storage anomalies

These data for the period January 2011 to July 2017 were in text format and were first sub-setted by selecting the geographical coordinates of Zimbabwe and then saved as comma delimited (CSV) files in MS Excel and processed in Quantum GIS (QGIS). The CSV tables were added in QGIS for conversion to point maps showing groundwater levels. After converting the CSV files to points, the layers were saved as shapefiles in a GIS. The data were later split into dry and wet season, covering April–October and November–March, respectively.

Preprocessing of GRACE data involved filtering out noise and correcting for atmospheric and oceanic effects (Yin et al., 2022; Verma and Katpatal, 2020). Validation of GRACE data was not performed in this study due to previously established correlations with in-situ data (Verma and Katpatal, 2020). Ordinary kriging assumes stationarity and isotropy in the spatial data, which may not always hold true in heterogeneous terrains (Foroumandi et al., 2023). In order to map the spatial variations of groundwater anomalies for individual months, the study used ordinary kriging. The monthly interpolated maps were merged for each season from 2011 to 2017. The resultant raster maps showing average groundwater anomalies for each season were combined into a dataset, which was then averaged out to give the final long-term average seasonal storage anomaly changes.

RESULTS AND DISCUSSION

Spatial and temporal variations in groundwater thickness during wet seasons

Figure 4 shows groundwater level fluctuations with respect to the mean water table level anomalies during the seasons from 2011 to 2017.

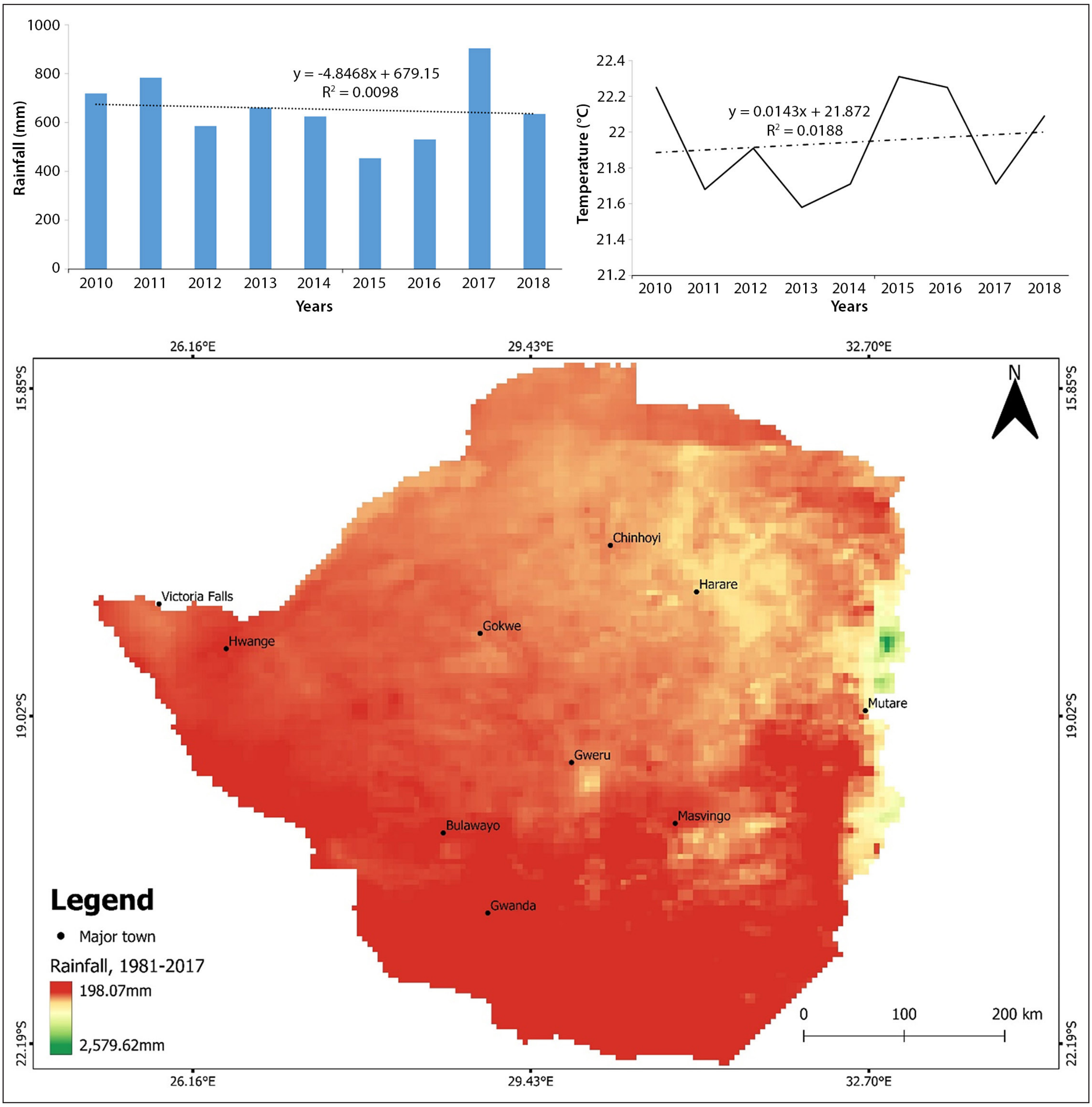

Figure 5. Zimbabwe's mean annual rainfall (top left graph) and temperature (top right graph) time-series from 2010 to 2018, and spatial variation of average annual rainfall from 1981 to 2017 (bottom map)

During 2011, 2012 and 2017 there were high groundwater level anomalies in the north west of the country. Almost 90% of the country had high groundwater level anomalies in 2014 and 2015. In 2014, almost three-quarters of the country had a groundwater level anomaly above 0.05 m of the mean water table whilst the rest of the country had positive, lower levels of groundwater anomalies. In 2015, high groundwater level anomalies were observed on the northern side and the whole country experienced positive groundwater values. In 2013, there were moderate groundwater level anomalies and the country experienced negative groundwater anomaly values. In 2016, there were high groundwater anomalies in the southern parts of the country and other parts of the country experienced negative values representing low groundwater anomalies. This followed fluctuations in rainfall amounts received (Fig. 5). Generally, northern parts of Zimbabwe have higher hydraulic transmissivity rates than the rest of the country, hence experience high groundwater level anomalies in most years (Muzenda et al., 2019).

Figure 6 shows the temporal variation of groundwater thickness during wet seasons. Four out of the seven wet seasons studied had groundwater level anomaly above the long-term average.

Dry season spatial and temporal variations in groundwater thickness

Figure 7 shows that groundwater thickness was high in the north west of the country during the 2011, 2012 and 2014 dry seasons. In 2013, the country experienced moderate to low ground water level anomalies but this was mainly negative for the whole country. For the years 2015, 2016 and 2017 there were low groundwater level anomalies in the northern parts of the country and high groundwater level anomalies in the southern parts, though 2017 had positive values.

The dry season experienced negative groundwater values in almost 60% of the seasons, whereas in 40% of the seasons groundwater levels were above the long-term average (Fig. 8). This may be

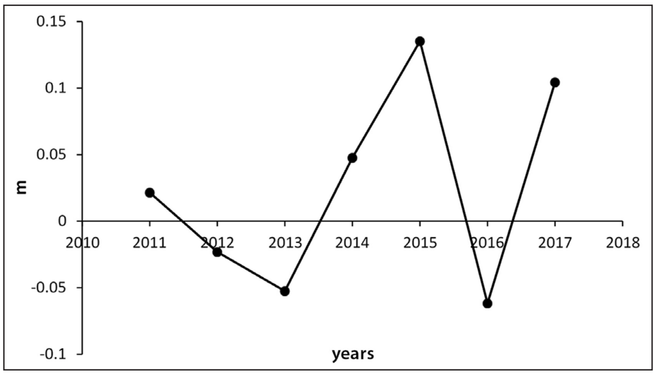

Figure 6. Temporal variations of total groundwater storage anomaly during the wet seasons from 2011 to 2017. The data indicate a significant increase in groundwater levels during the wet seasons of 2014 and 2015.

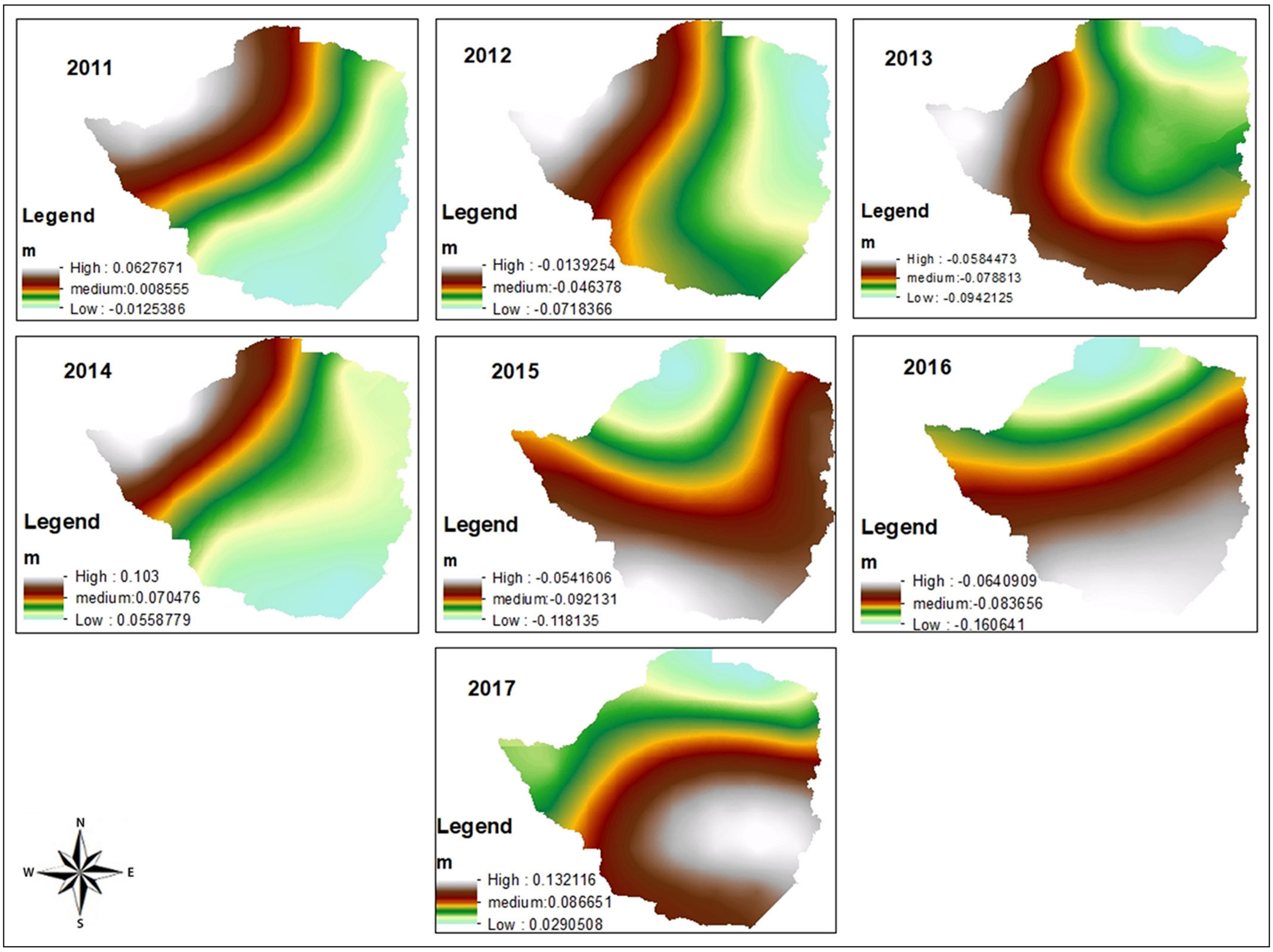

Figure 7. Dry season groundwater storage anomaly changes for the year 2011 to 2017

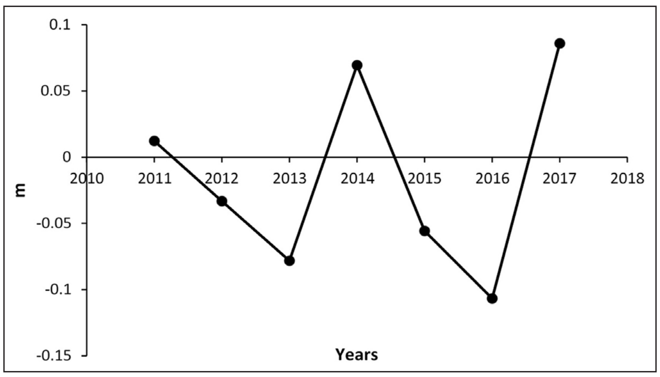

Figure 8. Temporal variations of groundwater anomalies during dry seasons, 2011–2017. The data indicate positive groundwater levels during the dry seasons of 2011, 2014 and 2017.

attributed to differences in geological and climatic conditions that may give the respective aquifers different water retention rates (Alghafli et al., 2023; Bonsor et al., 2018).

The negative values during the dry season shown in Fig. 7 are a result of the decrease in the country's annual rainfall and increasing temperature (Fig. 5). Temperature showed an increasing trend while rainfall showed a slight decreasing trend. Rainfall across the country varies spatially from a minimum value of approximately 200 mm/year to a maximum of nearly 2 500 mm/year. Most of the country receives low rainfall, hence there is poor groundwater recharge.

Precipitation in the southern parts has decreased by about 1% per decade (Chikodzi et al., 2014). In addition, the results are similar to those from other studies carried out in Zimbabwe (Chikodzi, 2013b). This is with the exception of the northern region, which shows a negative long-term trend in groundwater level anomaly. The depletion of groundwater in Zimbabwe is similar to other African regions, as observed by Arabameri et al. (2019) using GRACE data. This is attributed to a decrease in precipitation (Arabameri et al., 2019). These results demonstrate that GRACE data are useful for monitoring groundwater depletion in arid and semi-arid catchments. Therefore, this study's findings are useful for sustainable management of water resources. The correlation coefficient between GRACE-derived groundwater storage anomalies and in-situ measurements was found to be 0.75, indicating a strong relationship (Yirdaw and Snelgrove, 2011). Regions with declining groundwater levels may face increased water scarcity, necessitating targeted water management interventions (Adams et al., 2022; Quandt et al., 2022).

CONCLUSION

This study mapped the spatial and temporal dynamics of groundwater storage anomalies in Zimbabwe using GRACE satellite data for the dry and wet seasons from 2011 to 2017. Groundwater storage anomaly data were integrated into a GIS environment to produce maps showing seasonal changes in water thickness from the long-term mean. Research findings reveal that 57% of the dry seasons had a decreasing trend in groundwater levels in most areas. Groundwater levels were increasing in almost 57% of the wet seasons studied. The results show that groundwater storage responded strongly to precipitation and temperature variability. In spite of the coarse spatial resolution of GRACE data, this quick and simple approach appears to be appropriate in monitoring the dynamics of groundwater storage in data-scarce regions. Overall, the use of satellite measurements enables hydrologists to move beyond the point-based observations provided by borehole networks to basin-wide measurements of groundwater storage. Hence, GRACE satellite data can reliably be used in hydrological modelling in the absence of ground observations. Policymakers should consider investing in the development of local groundwater monitoring networks to complement satellite data. Future research should focus on integrating GRACE data with other remote-sensing techniques and ground-based measurements to improve the accuracy of groundwater assessments.

AUTHOR CONTRIBUTIONS

MC – methodology, data collection, analysis and writing of the draft manuscript. NM – research conceptualisation and design. HM – interpretation of results, revision and submission of manuscript after review. All authors approved the version of the manuscript submitted for review and final publication.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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