

## Is GRACE Data Capable of Simulating The Groundwater Level Fluctuation in Anuradhapura Region of Sri Lanka?

Fernando G.S.T.M.<sup>1\*</sup> and Bandara R.<sup>2</sup>

<sup>1</sup> Department of Remote Sensing and GIS, Faculty of Geomatics, University of Sabaragamuwa, Sri Lanka

<sup>2</sup> Department of Surveying and Geodesy, Faculty of Geomatics, University of Sabaragamuwa, Sri Lanka

[\\*fernandosuzanne2@gmail.com](mailto:*fernandosuzanne2@gmail.com)

**Abstract:** Under climate change and increasing water demands, groundwater has become a vital resource to satisfy most of the domestic and agricultural water requirements, especially in dry zones. It is advantageous to use satellite techniques for sustainable groundwater management, but gravitational satellites like the Gravity Recovery and Climate Experiment (GRACE) satellite are typically used in larger countries due to their coarse resolution. This study addresses this problem by assessing the capability of GRACE data in tracking groundwater storage changes in a smaller region like Anuradhapura, Sri Lanka. Groundwater fluctuation is assessed using Groundwater Storage Anomalies (GWSA) derived from the GRACE satellite and the Global Land Data Assimilation System (GLDAS) datasets. This study also compares climate variables using statistical methods to assess accuracy and reliability. The study period spans from 2003 to 2016, capturing long-term trends and seasonal variations in groundwater dynamics. Analysis reveals two prominent peaks in groundwater levels occurring around March and August, coinciding with rainfall patterns characteristic of the dry zone in Sri Lanka. Intensive rice cultivation during the Yala season (March to August), when groundwater removal is increased and water supplies become more dependent on groundwater, contributes to groundwater depletion, while rainfall infiltration during the Maha season (October to February) replenishes aquifers. Results also indicate that GRACE-based groundwater storage anomalies exhibit a significant increasing interannual trend of groundwater fluctuation with a rate of 0.1722 mm per annum. Polynomial regression analysis and Partial Least Squares Regression (PLSR) modeling are employed to validate the GRACE-derived GWSA changes based on GWSA trends and inputs of climate variables. Results indicate higher accuracy in GWSA estimation using PLSR compared to average fluctuation trends. The adjusted  $R^2$  values obtained for PLSR results present more than 0.9 for validating years, highlighting the potential of GRACE data to monitor and forecast groundwater dynamics.

**Keywords:** GRACE, Groundwater fluctuation, Groundwater Storage Anomalies, Partial Least Square Regression (PLSR), Sri Lanka

## **Introduction**

Groundwater, a vital natural resource hidden beneath our feet, plays a critical role in sustaining ecosystems and number of communities worldwide. In Anuradhapura, Sri Lanka, a city that has a long agricultural and social history and nestled within the dry zone, groundwater takes on an even greater significance. It irrigates fertile fields, meets the water demand of its growing population and satisfies most of the domestic water requirements in day-to-day life.

The rapid increment of water demand of growing population, unsustainable extraction during intensive agricultural practices and industrial activities and the climate variability, poses considerable pressure on the available groundwater resources in Sri Lanka. The industrial sector, in particular, heavily depends on deep wells due to their cost-effectiveness, safety, quality and the ability of managing autonomously (Bandaranayake, 2021). The rapid and unplanned expansion of agro-wells has been a cause for groundwater related problems, mainly due to the absence of appropriate hydrogeological assessments. As a result, farmers have started extracting groundwater at high rates, ranging between 27 m<sup>3</sup>/hour and 45 m<sup>3</sup>/hour, which may contribute to conflicts arising from overexploitation of groundwater resources at local or regional scales (Herath, 2007). However, research conducted on groundwater status in South Asia, including Sri Lanka, predicts about a potential of 10% of reduction in groundwater recharge by the 2050s due to climate change, which alternatively implies that there will be an inadequacy of groundwater for the future water demands in the country (Clifton et al., 2010). It is at its highest importance to manage the sustainability of groundwater resources especially in regions where surface water sources are limited or unreliable.

Understanding the dynamics and fluctuations in groundwater levels is critical for effective management and sustainable use of groundwater resources. In previous years, conventional methods like Groundwater exploration surveys were used. In the context of Anuradhapura region, groundwater monitoring has traditionally relied on a network of wells to obtain measurements. However, this approach has limitations in terms of spatial coverage, labor intensiveness and cost-effectiveness.

In recent years, remote sensing techniques have been popular for assessing and monitoring groundwater resources. These techniques utilize satellite-based observations to provide spatially distributed information on various hydrological parameters, including

groundwater levels. Remote sensing offers several advantages over traditional monitoring methods, including its ability to cover large areas, provide regular and reliable measurements, and provide insights into inaccessible or remote regions.

#### **a. Problem Statement**

In Sri Lanka, the monitoring of Groundwater Storage (GWS) is crucial for effective water resource management. However, in present, the country doesn't have adequate and necessary datasets for GWS estimation/monitoring. Traditional monitoring methods which are currently practiced in Sri Lanka, while effective, are resource-intensive, requiring significant manpower and material resources. This presents a significant problem as accurate and comprehensive GWS data is essential for informed decision-making regarding water availability and sustainability. As an alternative to the conventional methods, the use of satellite-based observations for hydrological information provides reliable accurate solutions, while offering advantages such as wide spatial coverage, cost-effectiveness, and non-invasive monitoring. Therefore, the research contributes to the economic sustainability in Sri Lanka by investigating the potential of using satellite-based observations to enhance GWS estimation accuracy and efficiency.

#### **b. Aims and Objectives of The Research**

Against the above-mentioned backdrop, this dissertation has endeavored to assess the efficacy of GRACE (Gravity Recovery and Climate Experiment) data in simulating groundwater level fluctuations in the Anuradhapura region, Sri Lanka.

Main objective:

- To assess the capability of GRACE Data to track the Ground Water level fluctuation in Anuradhapura area.

## **Literature Review**

### **a. Introduction**

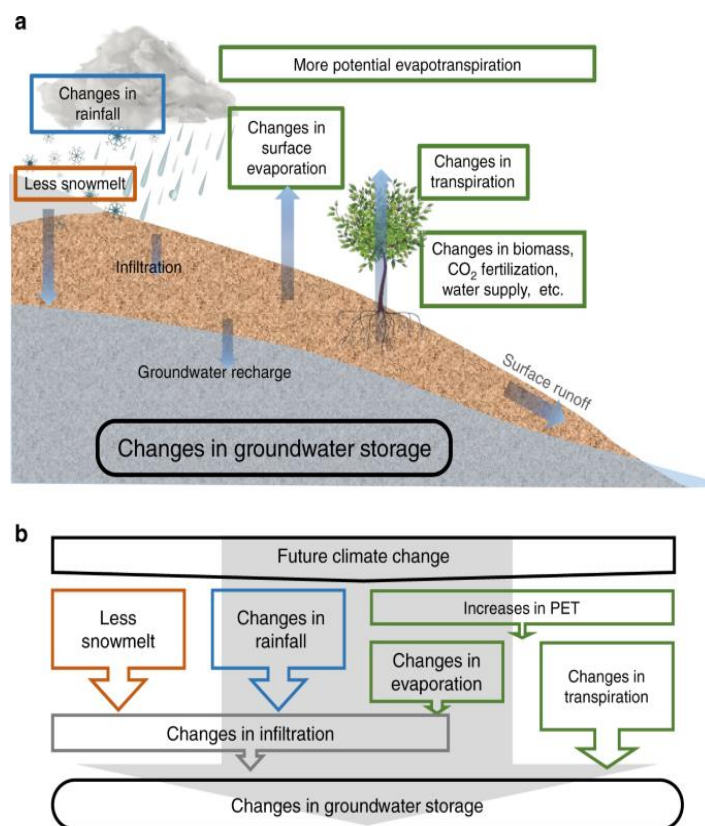
This literature review aims to assess and discuss the existing and relevant research on groundwater level monitoring and Ground Water Storage (GWS) analyses with a particular focus on recent developments and methodologies. Furthermore, it elaborates the theoretical framework of key concepts related to this study. The first section reviews the information about conventional methods and the utilization of satellite technologies for groundwater monitoring and the advantages and disadvantages of the methods in terms of spatial coverage, cost-effectiveness and monitoring capabilities. It also addresses the challenges associated with the coarse resolution of satellite data and the necessity of using downscaling techniques to enhance the spatial resolution of satellite data, for accurate assessments of groundwater resources at smaller scales. It also discusses the errors and precautions associated with downscaling methods, which is essential in obtaining accurate predictions of results. At last, this chapter discusses the application of mathematical equations, particularly Partial Least Squares Regression, for groundwater level estimation. It highlights the effectiveness of statistical models in dealing with complex relationships between various factors influencing groundwater dynamics.

### **b. Ground Water Level Estimation and Conventional Methods**

Groundwater is recognized as a potential water resource for domestic uses, small scale commercial and industrial purposes, and small-scale agricultural purposes (Panabokke and Perera, 2005). As per the previous studies, groundwater resource has already been deteriorated in many places in Sri Lanka due to improper management. Anuradhapura, an agricultural heartland in Sri Lanka, has a groundwater resource which has recently found to be polluted due to excess application of agrochemicals (Rajapaksha and Rajendran, 2022). Furthermore, studies have found that shallow ground water is currently been under threat due to over-extraction. This over-exploitation could lead to a long-term water scarcity issue particularly over the dry zone because groundwater is being limited in quantity (Bandaranayake, 2021). Therefore, effective groundwater level monitoring in this area is essential for assessing resource availability, identifying trends, and informing management decisions.

Human groundwater withdrawals, such as irrigation and domestic/industrial uses, play a significant role in groundwater level changes. There is a great need of controlling the

excessive groundwater extraction to use groundwater storage effectively. Rather than this, global climate change, has been identified as the other main cause of groundwater level reduction in certain regions. Hu et al. (2019) states that there is a high impact of climate variables such as precipitation, temperature, evapotranspiration, snow water equivalent and soil moisture on groundwater levels. Rising air temperatures and related meteorological events can affect the changes of precipitation, groundwater recharge and surface runoff, leading to changes in groundwater storages. Bandaranayake (2021) states that the groundwater volume of Sri Lanka has been highly affected by the reduction of natural recharge which is mainly driven by the reduction of infiltration due to the increasing temperature. It has been found that modern (less than 50 years old) groundwater levels are very vulnerable to climate change (Lakshmi, 2016). With the rapid change of climate patterns, understanding the groundwater dynamics has become significant for sustainable resource management.



*Source: Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers (2020)*

Figure 1: Climate change impact on changes in groundwater storage

Bandaranayake (2021) states that continuous monitoring allows for early detection of declining groundwater levels, preventing overexploitation and ensuring long-term sustainability. The field of groundwater monitoring holds significant global significance, not only in research but also in water resource management. In earlier days, before the implementation of advanced satellite technologies, groundwater level was monitored using onsite measurements and geophysical methods. Using Piezometers, Pressure Transducers, Automated Water Level Monitoring, Manual Water Level Monitoring and Geophysical Surveys like Electrical Resistivity Tomography (ERT), Seismic and Ground-Penetrating Radar (GPR) are some of them.

Furthermore, monitor groundwater levels using agricultural and household production wells with unknown perforation depths in the well casing provides even less valuable information. Dedicated monitoring wells are more expensive to build as it is planned specifically to measure groundwater levels. But it is advantageous to use dedicated groundwater monitoring wells as they can assess the impacts of groundwater extraction on each aquifer system, as well as the linkages and vertical gradients between them.(Fulton et al., 2002).

Electrical well sounding device and the pressure transducer are two examples for typical sounding devices which are currently available to measure groundwater levels. An electric well sounding device is a simple continuity detector. Pressure transducers is an expensive method which can be used to get continuous groundwater level measurements by connecting to a datalogger. Nwankwoala et al. (2022) used Vertical Electrical Sounding (VES) techniques to explore groundwater availability and layer thicknesses. It highlights the suitability of VES technique for exploring deeper groundwater resources due to the deeper penetration ability, but this technique only provides information along a single vertical profile, limiting the spatial coverage. With the development of technology, new groundwater monitoring techniques were introduced which required less amount of human interference. A recent study in Pakistan (Jadoon et al., 2023) used a network of low-cost groundwater sensors which were installed in aquifer recharge wells. This is a smart and resource efficient groundwater monitoring system which takes the real-time groundwater level measurements remotely and minimize the frequency of physical visits. But the high cost of these automated groundwater monitoring techniques has been a significant barrier to their implementation in developing countries like Sri Lanka. According to the previous studies, it can be concluded that the most of the methods are lack of spatial or temporal

resolution for the requirements and are financially untenable. In the context of Sri Lanka, where groundwater plays a pivotal role in agricultural productivity and water security, robust monitoring systems are critical for informed decision-making (Bandaranayake, 2021). The country currently practices several groundwater monitoring efforts, utilizing networks of observation wells and data logging systems.

### **c. Use Of Satellite Data – GRACE Mission**

It is extremely difficult to estimate terrestrial water resources due to the scarcity and expensiveness of in situ measurements which are used for quantifying the components of hydrological equations. These measurements are often not enough to capture the spatial heterogeneity of the landscape and has time limitations. Because of this, satellite remote sensing has become an obvious choice. The global coverage and temporal repeat data acquisition ability of satellite observations has become the major reason for this (Lakshmi, 2016). Over the past few decades, studies have proven the importance of satellite data in groundwater level monitoring because it allows for the assessment of groundwater resources over large areas and provides a synoptic view of groundwater-related processes (Springer et al., 2023). Satellite data is an invaluable resource because of its wide spatial coverage, cost-effectiveness, and non-invasive monitoring. It provides much relevant information about conditions around the globe at a spatial and temporal resolution of practical significance (Lakshmi, 2016). Springer et al. (2023) has comprehensively presented the strengths and weaknesses of several remote-sensing techniques that are generally used for GW research. Radar altimetry (RA) is a technology that was initially developed to evaluate ocean topography by continuously measuring the distance between the Earth's surface and the sensor on the satellite, but is now widely used to monitor inland water bodies. It is globally available across time and its coarse temporal resolution (between 10 and 35 days) is not a significant disadvantage for groundwater monitoring because low water periods often continue longer than high water ones. Thermal Infrared (TIR) images is another technique which provide indirect information on groundwater movements using the rise of thermal anomalies with respect to the surrounding temperature. TIR space-based images is useful to understand the functioning of groundwater reservoirs and their relationship with surface conditions, specially, local atmospheric conditions. The major disadvantage of using these images is its actual spatial resolution (from ~100 m to 5 km). This is also planned to be minimized by the next generation of TIR missions at higher spatial resolution such as Thermal infraRed Imaging

Satellite for High-resolution Natural resource Assessment (TRISHNA) and the Copernicus' Land Surface Temperature Monitoring (LSTM) mission.

InSAR data is another technology that can be used to obtain information on GW storage variation indirectly from ground deformation. This ground deformation mapping is conducted via space-based radar sensors, such as ERS, RADARSAT, ENVISAT and ALOS. Furthermore, it has proved that compaction measurements and land subsidence detection from InSAR techniques have the possibility to provide high-resolution details on aquifer dynamics. Therefore, combining GRACE and InSAR data gives accurate results in a more local scale while GRACE estimation of GW changes can only be used for very large aquifers and with strong GW anomalies (Springer et al., 2023).

Amongst these and other remote sensing techniques, gravitational measurements found to be giving reliable and rapid information of terrestrial water storage changes. It has been found that groundwater behavior and groundwater aquifer storage can be estimated by combining satellite remote sensors and satellite gravitational surveys with ancillary data analysis (Klemas & Pieterse, 2015). Among limited number of gravitational satellite data, GRACE can be used to quantify changes in groundwater resources and identify possible climatic and anthropogenic drivers. Comparing to other types of hydrological schemes, GRACE has the capability to provide real-time spatiotemporal variations of water storage. It generally includes the vertically integrated measurements of groundwater, surface water, soil moisture, snow water, vegetation water, etc. at the precision of tens of mm of equivalent water height at large scale (Jiang et al., 2014). Total terrestrial water storage cannot be measured as individual components such as surface water and soil moisture using satellite and ground-based techniques. Therefore, lack of observations, systematic monitoring and having no integrated measurement of TWS has caused TWS to be completely unknown at regional and global scales (Ning et al., 2014).

The Gravity Recovery and Climate Experiment (GRACE) 2002 - 2017 and GRACE Follow-On (GRACE-FO, 2018 onwards) is the first joint satellite mission of NASA and the German Aerospace Center -DLR, to provide exclusive data on temporal variations in Terrestrial Water Storage (TWS). It can measure changes in total, column-integrated TWS from space by using tiny changes in the Earth's gravity field. These changes are occurred due to mass changes in hydrosphere, atmosphere, biosphere, oceans and inside the solid Earth. GRACE gravity solutions generally provide TWS anomalies because contributions



in atmospheric and oceanic mass changes are removed during GRACE data processing (TWSA) (Springer et al., 2023).

GRACE data is particularly used in monitoring large aquifers and areas with strong groundwater anomalies. Satellite data, such as GRACE-derived Total Water Storage anomalies, can be used to estimate differences in groundwater storage by considering other water storage compartments. However, GRACE has no vertical resolution and because of that, the vertically integrated TWS change (TWS) estimated by the GRACE datasets consist of changes in Soil moisture (SM), Snow water equivalent (SWE), surface water reservoir storage (SWRS) and groundwater (GWS) (Hu et al., 2019). Efficient integration of data and theoretical models are required to measure subsurface ground water which cannot be measured directly from space (Becker et al., 2010). Thus, GWS can be calculated as the residual of the following water balance equation:

$$GWS = TWS - SM - SWE - SWRS$$

Anuradhapura, located in North Central province in Sri Lanka has a tropical monsoon climate characterized by distinct wet and dry seasons. The possibility of snowing in Anuradhapura is extremely unlikely due to its tropical climate influenced by its proximity to the equator, the Indian Ocean, and the low elevation of the region. Therefore, in this study, the snow water equivalent SWE is neglected as it cannot make a significant change to the major result and the water balance equation is simplified as following:

$$GWS = TWS - SM - SWRS$$

When using data of point locations, it is required to be interpolated to get a common value for the whole area. Sokolchuk and Sokáč (2022) considered four methods of spatial interpolation: method of inverse distance weighted (IDW), Spline interpolation, triangulation (TIN) and Kriging. They determined that the IDW method gives better results for the generalization of hydrological data over the studied area, with smooth transitions and small errors. But the data provided by remote sensing satellites limits the usability because of the coarser resolution.

#### **d. GRACE Data Downscaling**

Although there are many remote sensing applications for assessing water resources and water quality in present, spectral and spatial resolution limitations of current sensors has limited the wide range of satellite data applications (Marapana, 2017). Many satellite images have coarser resolutions which is incapable of meeting the requirements that are

expected by the geospatial interpretations. As a solution, downscaling those images from coarser resolution to finer resolution is possible undertaking different techniques. However, all available downscaling techniques do not fit with the GRACE downscaling because the entire concept is totally different from satellite images downscaling. General Satellite images are measurements from the electromagnetic spectrum intensity that is sensed by a sensor. But gravitational measurement is relying entirely on the gravitational pull. Gravitational satellite data do not have a direct relation with the electromagnetic spectrum. Ouma et al. (2015) has integrated time-variable Gravity Recovery and Climate Experiment (GRACE) gravimetric measurements and Global Land Data Assimilation System (GLDAS) land surface models (LSM) and concluded that it is reliable to use the above data for studying groundwater storage changes. It has used the water balance equation and parameters to estimate groundwater storage variability and linear regression to analyze long-term trends in the data. It also states that the accuracy of the results might have been affected because the size of the study area is smaller than the recommended size for GRACE data applications. The study does not consider the impacts of climate change and anthropogenic factors on groundwater variations, which is recommended to be considered in future studies.

According to Lakshmi (2016), terrestrial water budget computations which are using satellite data should be carried out over large areas ( $10^3$  to  $10^5$  km<sup>2</sup>) and long time periods (years to decades). When applying Remote Sensing and GIS into groundwater monitoring, the used satellite data should be in a considerable resolution. This condition is also identified by some researchers as it prohibits the most of hydrological uses which can be achieved from GRACE TWS product. GRACE Data should be disaggregated when used for a smaller region like Sri Lanka.

GRACE data has a coarse resolution of 1 degree, which limits its application for local-scale water resources management. Ning et al. (2014) has found a statistical approach to downscale gridded GRACE product to a finer resolution of  $0.25^\circ$  using statistical regression methods. Furthermore, it has found that GRACE TWS (Terrestrial Water Storage) has a good relationship with storage change obtained by the water balance equation. This approach has been applied and validated for the same study area used in this research, Anuradhapura region, Sri Lanka (Marapana, 2017).

### **e. Statistical Analysis for Groundwater Level Estimation**

It has been found that there is a high influence of meteorological variables such as, precipitation and evapotranspiration to the fluctuation of groundwater level. These variables can be used to model and predict the groundwater levels. Statistical analyses can be used in data-driven models to estimate groundwater level fluctuations based on various input factors. Statistical regression is important in assessing groundwater levels because it allows for the estimation of groundwater resources and the prediction of future trends. Regression models, such as feed-forward artificial neural networks, have been found to be effective in monitoring and predicting groundwater characteristics, particularly groundwater levels (Chakraborty et al., 2022). Apart from this, in number of previous studies, partial least square regression has given more accurate estimations among other statistical techniques. Khatri et al. (2021), describes the use of PLS regression modeling for water related analysis of different kinds of water samples and it describes the importance of PLSR for assessing hydrologic components because of its multicollinearity and multidimensionality.

Pirouz (2006) states that, Partial least squares (PLS) regression is a powerful statistical technique that can handle high-dimensional data and complex relationships between predictors and response variables. It performs least squares regression on a smaller set of uncorrelated components which were obtained by predictors, instead of on the original data. Partial least squares is a covariance-based statistical method which is designed to deal with multiple regression when data has small sample, missing values or multicollinearity. PLS regression is especially used when the predictors are highly collinear or when there are more predictors than observations. Unlike multiple regression, PLS does not assume that the predictors are fixed which means the predictors can be measured with error. This makes Partial least squares regression more robust to measurement uncertainty on both real data and in simulations. Partial least squares regression is an extension of multiple linear regression and has many of the same assumptions (Pirouz, 2006).

According to the previous researches discussed in this chapter, it is very effective for the economic sustainability to use satellite data for groundwater level monitoring rather than conventional methods. In satellite data, gravity anomalies are widely used for hydrological assessments worldwide. Not like countries that are huge in spatial area, for smaller regions, the coarse resolution of GRACE data has been a limitation. Due to that, it is notable that downscaled GRACE data can be effectively used for the statistical approaches for groundwater level estimation in smaller regions. Furthermore, it can be concluded that the

Partial Least square regression is a valuable tool for understanding and predicting the impact of climate variables on groundwater fluctuations as it has been found to achieve higher accuracies in predicting groundwater level changes compared to traditional mathematical models. This study will overcome the limitations of manual and high-cost monitoring methods, data scarcity, inapplicability for smaller areas and the incapability to achieve resolution requirements of results. To date, this methodology is not tested and validated for a smaller region like Sri Lanka.

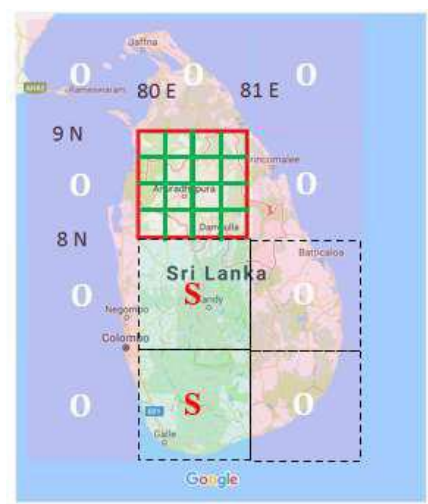
## Methodology

### a. Study Area:

The study area is mainly Anuradhapura in North Central province, which belongs to the dry zone of Sri Lanka, covered within 8°-9° Northern latitudes and 80°-81° Eastern longitudes. Anuradhapura has a tropical climate, hot all year around with a rainy season from October to December and a in April or sometimes May.

The average temperature of the coldest month (January) is of 26.0 °C (78.8 °F), that of the warmest month (April) is of 29.7 °C (85.5 °F). It has a mean annual temperature of 27.3°–28.3° C and mean annual rainfall of 1247–1419 mm. The highest amount of the precipitation (74%) is received during the second inter-monsoon rain, between October to November, and the northeast monsoon rain, between December to February. Precipitation ranges from 11 mm (0.4 in) in the driest month (June) to 260 mm (10.2 in) in the wettest one (November). The rest of the year reports a dry climate, while late August to early September marks the peak of the drought.

The highest evapo-transpiration (>6 mm/day) of this area is usually between the dry period, from May to September. The low-land undulating topography of this area varies between 50 to 400 m above the mean sea level (Imbulana et al., 2021).



O - More sea areas are included

S - More slope areas are included

Figure 2: Selected GRACE pixel location

The selected study area contained of 16 pixels after disaggregation. (GRACE  $0.25^\circ = \text{GRACE } 1^\circ / 16$ ). Among these, Pixel no. 9 was selected for further work because that pixel was successfully validated for the disaggregation methodology which was utilized in this study.

**b. Research Methodology:**

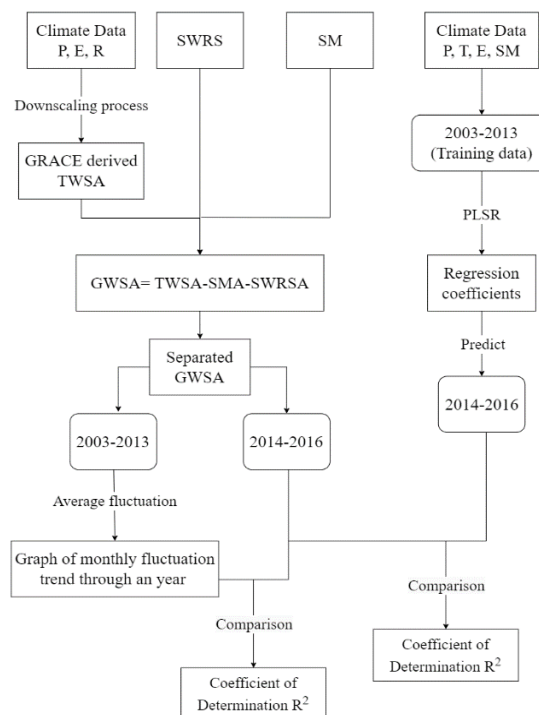


Figure 3: Methodology flow chart

This research attempts to check the accuracy of downscaled GRACE data using two separate techniques; comparing with annual groundwater level fluctuation trend and Partial Least Square Regression.

The downloaded data should be processed and downscaled in the beginning. For downscaling, Precipitation, Evapotranspiration and surface runoff data of the specific area was used as in following water balance Eq. (1).

$$\Delta S_i = P_i - ET_i - R_i \dots \dots \dots (1)$$

In this,  $P_i$  is the precipitation,  $ET_i$  is the evapotranspiration, and  $R_i$  is the Surface Runoff in the  $i^{\text{th}}$  month and  $\Delta S_i$ , the terrestrial water changes which was required to obtain the disaggregated GRACE Data value using the following previously validated disaggregation equation for the study area.

$$\text{GRACE } (TWS_i)_{0.25^\circ} = -2 \times 10^{-7} \Delta S_i^2 + 0.0146 \Delta S_i - 0.8665 \dots \dots \dots (2)$$

The downscaled TWSA data, Soil moisture (SM), Snow water equivalent (SWE) and surface water reservoir storage (SWRS) was used to calculate groundwater storage anomalies (GWSA).

$$\text{GWS} = \text{TWS} - \text{SM} - \text{SWRS} \dots \dots \dots (3)$$

The obtained GWSA values were then compared with average monthly groundwater level values and predicted values by Partial Least Square regression which was trained by Precipitation, Temperature, Evapotranspiration and Soil Moisture climate data.

**Results and Discussion**

**a. Results Of Average Trend Line Comparison:**

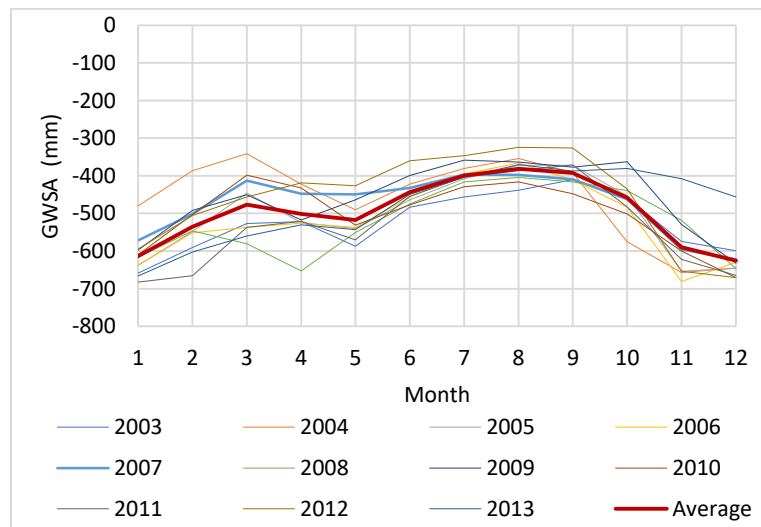


Figure 4: Year over year GWSA Fluctuation and the average trend line of the 11 years in the study area

There are two high groundwater level points in the graph, indicating periods where groundwater is closer to the Earth's surface - one around March and another around August. Anuradhapura is located in the dry zone, where most of the rain falls during two seasons: the inter-monsoon rains between October and November, which causes a depletion due to the high intensity and short duration (Imbulana et al., 2021). The northeast monsoon rains from December to February likely explains the rise in groundwater levels from January to March due to long duration which has sufficient time to infiltrate through soil layers (Imbulana et al., 2021). Anuradhapura is one of the most popular areas for rice cultivation with a great potential ability. (Jeewanthi et al., 2021). This intensive agriculture, particularly during the Yala season (March to August), could be the reason for groundwater level depletion from March to May. However, the graph shows another gradual rise from May to August. This might be due to the earlier April rainfall infiltrating and reaching the

underground aquifers. Marapana (2017) has suggested that there can be a two-month lag between rainfall and the water reaching the groundwater table. With the end of September and the beginning of the Maha season for paddy cultivation, there is a gradual decrement in groundwater level from August to December.

El Nino and La Niña, generally known as El Nino Southern Oscillation (ENSO), are coupled atmospheric ocean systems that originate in the tropical Pacific Ocean. These unusually warm (El Nino) and cold (La Niña) episodes affects to shifts in rainfall patterns in the world (Jayakody, 2015). The impact of La Niña on seasonal and monthly rainfall plays a huge role in predicting seasonal rainfall patterns. Sri Lanka has experienced a strong La Niña period during June 2007-April 2008 (Jayakody, 2015). Significant impact of North Eastern Monsoon rainfall is also profound over North central region of the country with a higher seasonal rainfall during La Niña events. Most of the previous studies found that rainfall anomalies during the La Niña seasons do not show a clear contrast in their temporal patterns (Hapuarachchi and Jayawardena, 2015). The increment of rainfall creates excess surface water runoff which results in groundwater level depletion. This could be the reason for the significant change in groundwater level in 2008 April (Adhikari et al., 2010).

Furthermore, this trend can be generally presented using a higher order polynomial equation which allows easy comparison with historical data. This can be used to assess whether the observed trends in groundwater storage align with the predictions made by the polynomial equation, providing validation and calibration for hydrological models and simulation results. It can be also used to extrapolate future trends in groundwater storage. By extending the equation beyond the observed data points, it can be used to forecast potential changes in groundwater levels and plan future hydrological conditions in the study area. Figure 5 perfectly visualizes the polynomial equation fitted 96% to the average fluctuation line.

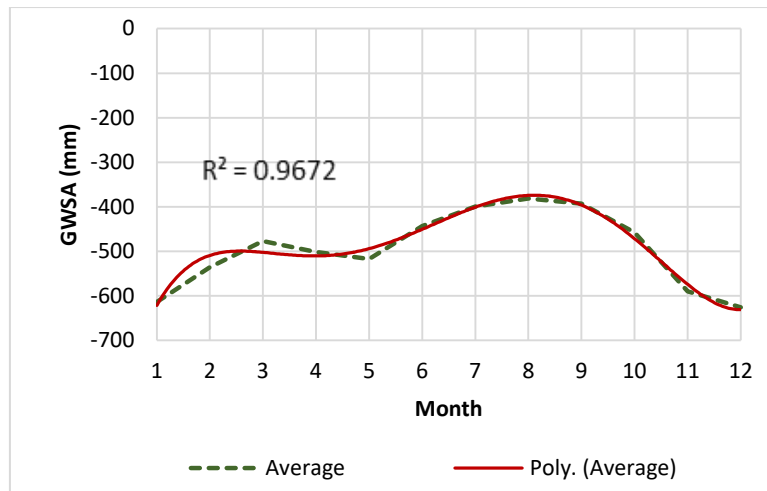


Figure 5: Higher order polynomial equation which fits well to the monthly groundwater level fluctuation

The average monthly groundwater level fluctuation through a year can be generally presented using the following Equation (4).

$$y = 0.1162x^5 - 3.8635x^4 + 46.139x^3 - 243.35x^2 + 573.59x - 994.02 \quad (4)$$

Figure 5 reveals changes in the direction of groundwater storage trends around February-March, April-May and in August. These inflection points may indicate shifts in hydrological conditions, such as droughts, periods of recharge or changes in land use practices. This polynomial trend equation was used to compare with the GRACE derived GWSA values. Following table 1 contains the results derived by downscaled GRACE Data and the average monthly GWSA values from 2003 to 2013.

Table 1: Comparison of Downscaled GRACE derived GWSA value with Average GWSA

	<b>Average (2003-2013) (mm/month)</b>	<b>GRACE (2014) (mm/month)</b>	<b>GRACE (2015) (mm/month)</b>	<b>GRACE (2016) (mm/month)</b>
Jan	-613.952	-476.917	-614.28	-573.742
Feb	-535.753	-400.454	-532.764	-473.592
Mar	-476.934	-344.827	-477.496	-400.867
Apr	-501.538	-355.101	-499.149	-387.388
May	-517.219	-462.344	-570.476	-546.744
June	-443.165	-380.951	-522.319	-536.642
July	-399.370	-337.893	-429.275	-459.486
Aug	-381.313	-342.117	-401.748	-428.094
Sept	-392.730	-348.819	-418.137	-383.687
Oct	-457.736	-474.385	-514.924	-366.864
Nov	-590.233	-609.659	-698.528	-443.775
Dec	-625.762	-703.870	-680.295	-448.944



R <sup>2</sup> Value		0.583	0.806	0.113
----------------------	--	-------	-------	-------

According to the R<sup>2</sup> values, it can be seen that the polynomial function of average fluctuation has been able to describe the 2014, 2015 and 2016 years 58%,80% and 11% respectively. 2016 year is more significantly different from the average fluctuation trend and the El Nino in 2016 could have been a reason for that (Kolusu, 2019).

It can be concluded that although the average trendline is not perfectly fits for precise numerical representation of fluctuations, it serves well in identifying the general direction of the trend. The challenge with relying on an average value is that, despite the overall consistency in fluctuations, climate conditions and various natural and human-induced factors may vary from year to year. Consequently, the validation data may display slight deviations from the average trend due to these changing conditions. These results can be further improved by using ground truth data for validation.

Apart from above mentioned reasons, it can be seen that there is an annual increment trend in groundwater levels which was not in the scope of this study. The following graph in figure 5 represents the inter annual trend from 2003-2013 and the linear trend equation which was found as  $y = 0.1722x - 506.09$ .

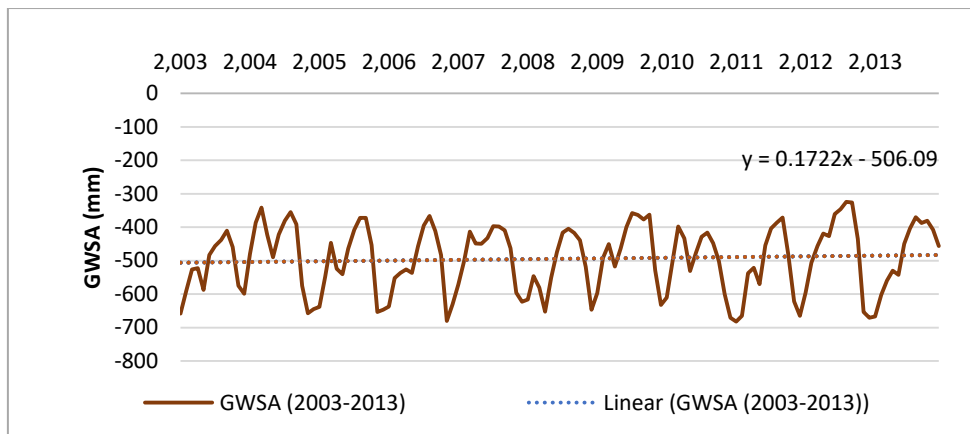


Figure 6: Inter annual trend of Groundwater fluctuation

The interannual variability in figure 6 could be a result of climate patterns in Sri Lanka that varies significantly from year to year. In some years, Sri Lanka may experience above-average rainfall, leading to increased groundwater recharge and higher groundwater levels. In other years, there may be below-average rainfall, resulting in reduced groundwater recharge and declining groundwater levels. Such interannual variability in precipitation and

other climate variables can impact the accuracy of groundwater storage level predictions (Abeyasinghe & Rajapakse, 2023).

Although figure 6, depicts a positive linear trend of groundwater level from 2003 to 2013 (training dataset), following figure 7 shows a different result.

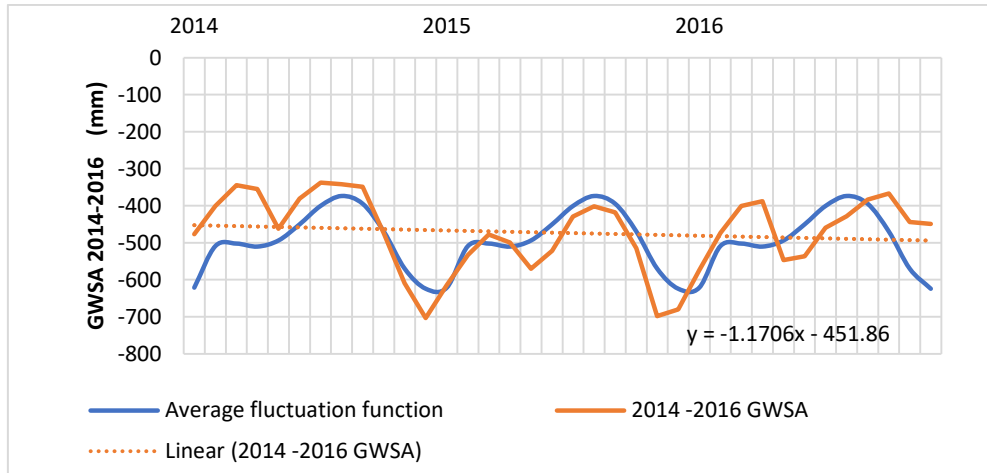


Figure 7: Comparison of validation data and its linear trend

Figure 7 includes the validation data from 2014 to 2016, which shows a decreasing linear trend. It can be seen that, the validation dataset has a decreasing linear trend, while training dataset has an increasing linear trend. This could also have impacted to the low adjusted  $R^2$  values between the GRACE derived data and average GWSA values. Apart from the interannual variability, the seasonal variability could also have been affected for this. Because, any variations in the timing, duration, or intensity of the monsoons can impact the overall groundwater availability and recharge rates (Abeyasinghe & Rajapakse, 2023).

Changing precipitation patterns due to climate change can also have significant impacts on groundwater resources in Sri Lanka. There are projections that Sri Lanka may experience changes in rainfall patterns, with increased intensity of rainfall events, changes in the duration of monsoons, and overall variability in precipitation. These changes can further impact groundwater recharge and availability, and may require adaptation strategies for sustainable groundwater management (Abeyasinghe & Rajapakse, 2023).

## b. Results Of PLSR

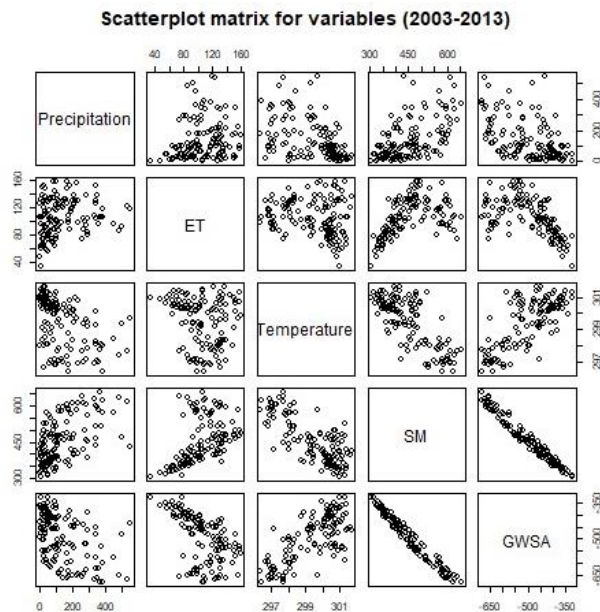


Figure 8: Scatterplot matrix of climate variables and GWSA

The scatterplot matrix in figure 8 was utilized to understand the relationship between climate variables (Monthly Precipitation; Evapotranspiration; Temperature; Soil Moisture) and GWSA. Prior to investigating the relationship between two quantitative variables, it is always helpful to create a graphical representation that includes both of these variables. According to this, Soil Moisture has a strong linear negative association with GWSA, because in general, this two has an opposite relationship. Groundwater discharges to the soil through seepage or evapotranspiration, contributing to soil moisture levels and groundwater storage is replenished through recharge when water not retained in the soil profile infiltrates downwards. Precipitation and evapotranspiration both show a negative relationship with GWSA. The amount and intensity of rainfall directly affect the rate of groundwater recharge. During heavy rainfall events, a significant amount of water may quickly run off the surface, resulting in reduced infiltration and recharge, leading to decreased groundwater availability (Abeyasinghe & Rajapakse, 2023). Evapotranspiration which refers to the combined processes of evaporation from soil and water surfaces and transpiration from plants, results the loss of water from the terrestrial ecosystem into the atmosphere. Due to that, the increment in ET potentially leads to a decrease in GWSA and vice versa. Monthly temperature does not have a wide value range, which is nearly constant, results a weak relationship with GWSA.

However, relying on the interpretation of a scatterplot is too subjective. Therefore, required more precise evidence is obtained by calculating Pearson correlation coefficient which

assumes that the relationship between the two variables is linear (Mindrila & Phoebe, 2021). Following are the correlation coefficients for each variable with GWSA.

$$\text{Precipitation} = -0.4758$$

$$\text{Evapotranspiration} = -0.55724$$

$$\text{Temperature} = 0.746857$$

$$\text{Soil Moisture} = -0.9815$$

These values clearly indicate the strong relationship between Soil Moisture and GWSA. Furthermore, this relationship is modelled using Partial Least Square Regression using the following function and the results of regression coefficients ( $a_i$ ) obtained is mentioned below.

$$\text{GWSA} = a_0 + a_1 \text{ PA} + a_2 \text{ TA} + a_3 \text{ EA} + a_4 \text{ SMA}$$

$$a_1 = 0.08196762$$

$$a_2 = 2.21623702$$

$$a_3 = -0.40537436$$

$$a_4 = -1.05277399$$

Using the trained PLSR model, GWSA values were predicted for 3 years for the validation.

Table 2: The PLSR predicted 2014 to 2016 GWSA values and the  $R^2$  values

	<b>2014 (mm/month)</b>	<b>2015 (mm/month)</b>	<b>2016 (mm/month)</b>
Jan	-490.635	-607.445	-563.562
Feb	-409.526	-521.463	-455.534
Mar	-335.493	-455.11	-362.648
Apr	-347.709	-472.118	-353.974
May	-477.189	-555.857	-529.199
June	-378.117	-508.127	-526.695
July	-328.226	-400.347	-448.803
Aug	-350.705	-379.987	-420.869
Sept	-347.643	-404.965	-374.025

Oct	-492.388	-510.521	-368.376
Nov	-609.046	-674.367	-457.354
Dec	-662.153	-665.166	-476.161
R <sup>2</sup> Value	0.98232	0.99402	0.93644

The table 2 includes the predicted 2014 to 2016 GWSA values in the unit of mm per month and the R<sup>2</sup> values which were obtained by comparing with the GRACE derived data. These values are highly correlated with GRACE derived GWSA values than the average fluctuation. The use of absolute climate data of each year rather than an average value could be the reason for the higher accuracy in this method.

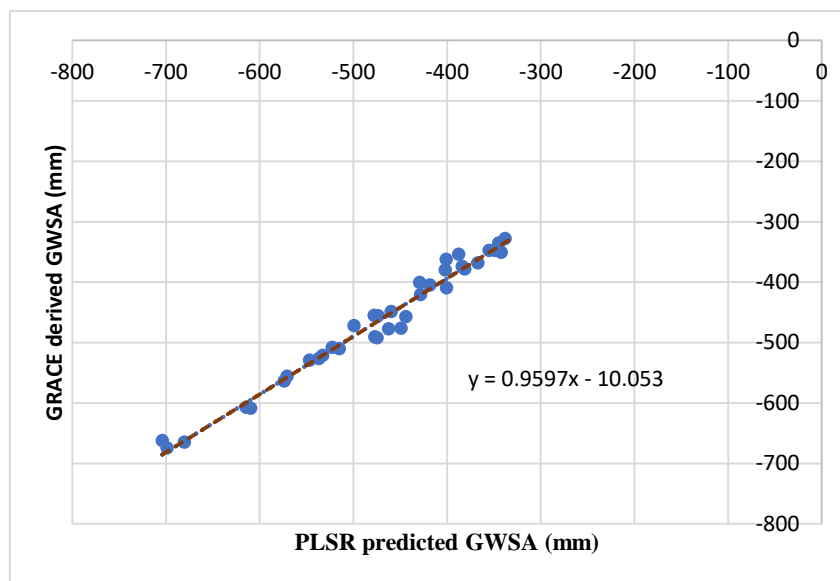


Figure 9: Relationship between GWSA obtained using PLSR and GRACE

The scatterplot in figure 9 depicts the relationship between GRACE-derived results and Partial Least Squares Regression (PLSR) predicted results, with a linear correlation equation of  $y = 0.9597x - 10.053$ . It is a key figure in assessing the capability of GRACE data to track the Ground Water level fluctuation in Anuradhapura area. This correlation coefficient of approximately 0.96 indicates a strong linear relationship between the two sets of data, suggesting that the PLSR model effectively predicts groundwater storage anomalies (GWSA) based on GRACE-derived observations. By achieving such a high correlation, the study demonstrates the efficacy of utilizing GRACE data in estimating GWSA, addressing the primary objective of the research. Furthermore, the tight clustering of data points around the regression line indicates the precision and accuracy of the PLSR model in predicting GWSA values. This ensures the reliability of the modeling approach and strengthens confidence in the research outcomes.

## Conclusion and Recommendation

Using statistical regression to assess GWSA using GRACE has done in many developed countries such as India, China and Canada which are bigger in spatial area. This study was an attempt to check the applicability of GRACE data to a smaller region like Sri Lanka. The study mainly focused on assessing the capability of GRACE Data to simulate the Ground Water level fluctuation. In this study, groundwater changes over Anuradhapura region are analyzed and validated for the period of 2003–2016.

GWSA was derived from GRACE datasets and downscaled. The other required data for the analysis were mainly taken from GLDAS dataset. Due to the scarcity of data, global datasets were utilized for this study. Although this methodology had not been previously applied in Sri Lanka, using a global dataset for the first time seemed a reasonable approach. Obtaining meteorological data from the meteorological department for a period exceeding 10 years proved challenging and costly. Therefore, it is recommended to establish and maintain an accurate and comprehensive database of hydrological and meteorological data in Sri Lanka.

The performance of the GWSA was evaluated using two unique methods; the results from PLSR method and average monthly GW fluctuation. Anuradhapura in North Central province, belongs to dry zone in Sri Lanka, which experiences two of the three monsoonal rains; Northeast monsoon (December to February) and inter monsoon (October to November) rain. The monsoons have a great impact to the changes in temperature, precipitation, evaporation, soil moisture, and Groundwater level. Furthermore, it has found that the GWSA increases slightly over annual time scale. Among the two monsoons, the Inter monsoon has a groundwater depletion and Northeast monsoon has an increment in groundwater level. The annual GWSA in the study area has a general positive trend of 0.1722 mm/a. The increased groundwater was detected in this area which might have been caused by the increased precipitation of 0.1235 mm/a. The findings state that the comparison of average values method proves 60%,80% and 11% accuracy for 2014, 2015, 2016 years respectively.

Furthermore, this study used the Partial least square regression method to analyze the effect of climate variables to check the accuracy of the obtained results. The comparison with groundwater statistics from PLSR showed that the GRACE observations were a reliable tool to estimate GWS changes, which provide reliable and cost-effective scientific

reference for Hydrologic community for sustainable groundwater management. The PLSR model developed by GRACE-based GWSA and dependent variables (i.e., PA, TA, EA, and SMA) showed an acceptable performance in estimating monthly GWSA. The  $R^2$  of PLSR-GWSA reached 0.98, 0.99 and 0.93 in 2014, 2015, 2016 respectively. This concludes that PLSR model based on GRACE-based GWSA can be potentially used for forecasting groundwater changes with inputs of predicted PA, TA, EA and SMA. During the process; Partial Least Square Regression method has proved the accuracy of GRACE derived GWSA values better than average fluctuation trend method. Therefore, it can be concluded that downscaled GRACE derived GWSA product can be effectively applicable to assess the groundwater level fluctuations in North Central Province in Sri Lanka which was the primary objective of this research.

It is also important to note that this methodology has applied and validated only for a plain region without hilly areas. Similar procedure can be adapted to smaller regions without steep slopes in the other areas of the country. However, the GRACE-based GWS changes estimation still contains uncertainties caused by the errors in GRACE-derived TWS changes such as errors in the original GRACE products and the coarse resolution of GRACE. Another challenge is the limited groundwater well observations in Anuradhapura, which is a limitation in validating the GRACE-based GWS changes.

The accuracy of this study is mainly depended on the accuracy of the data used. Therefore, using more precise and reliable data sources could improve the accuracy of the results. Furthermore, it should be noted that the spatial variability of groundwater level dynamics was not focused in this study.

## References

- Abeysinghe, A. M. N. P. B., & Rajapakse, R. R. G. R. (2023). *Impacts on Groundwater Resources by rainfall variations due to Climate Changes in Sri Lanka*.
- Adhikari, S., Liyanaarachchi, S., Chandimala, J., Nawarathna, B. K., Bandara, R., Yahiya, Z., & Zubair, L. (2010). Rainfall prediction based on the relationship between rainfall and El Niño Southern Oscillation (ENSO). *Journal of the National Science Foundation of Sri Lanka*, 38(4), 249. <https://doi.org/10.4038/jnsfsr.v38i4.2652>
- Bandaranayake, K. (2021). *Considering future precipitation in delineation locations for water storage systems -Case study Sri Lanka*. Retrieved August 19, 2024, from <https://lup.lub.lu.se/luur/download?func=downloadFile&recordId=9040418&fileId=9040419>
- Becker, M., Llovel, W., Cazenave, A., Güntner, A., & Crétaux, J.-F. (2010). Recent hydrological behavior of the East African great lakes region inferred from

- GRACE, satellite altimetry and rainfall observations. *Comptes Rendus Geoscience*, 342(3), 223–233. <https://doi.org/10.1016/j.crte.2009.12.010>
- Chakraborty, M., Tejankar, A. V., Coppola, G., & Chakraborty, S. (2022). Assessment of groundwater quality using statistical methods: a case study. *Arabian Journal of Geosciences*, 15(12). <https://doi.org/10.1007/s12517-022-10276-2>
- Clifton, C., Evans, R., Hayes, S., Hirji, R., Puz, G., & Pizarro, C. (2010). *Water and Climate Change*. <https://doi.org/10.1596/27857>
- Fulton, A., Dudley, T., & Staton, K. (2002). *GROUNDWATER LEVEL MONITORING: WHAT IS IT? HOW IS IT DONE? WHY DO IT?* Retrieved February 19, 2024, from <https://www.countyofcolusaca.gov/DocumentCenter/View/4260/Series1Article4-GroundwaterLevelMonitoring>
- Hapuarachchi, H.A., & Jayawardena, I.M. (2016). Modulation of Seasonal Rainfall in Sri Lanka by ENSO Extremes.
- Herath, G. (2007). *The Study of the Management of Groundwater Resources in Sri Lanka. IGES: Sustainable Groundwater Management in Asian Cities-a final report on Sustainable Water Management Policy* (pp. 110–136). [https://www.iges.or.jp/en/publication\\_documents/pub/policyreport/en/654/08\\_chapter3-5srilanka.pdf](https://www.iges.or.jp/en/publication_documents/pub/policyreport/en/654/08_chapter3-5srilanka.pdf)
- Hu, Z., Zhou, Q., Chen, X., Chen, D., Li, J., Guo, M., Yin, G., & Duan, Z. (2019). Groundwater Depletion Estimated from GRACE: A Challenge of Sustainable Development in an Arid Region of Central Asia. *Remote Sensing*, 11(16), 1908. <https://doi.org/10.3390/rs11161908>
- Imbulana, S., Oguma, K., & Takizawa, S. (2021). Seasonal Variations in Groundwater Quality and Hydrogeochemistry in the Endemic Areas of Chronic Kidney Disease of Unknown Etiology (CKDu) in Sri Lanka. *Water*, 13(23), 3356. <https://doi.org/10.3390/w13233356>
- Jadoon, K. Z., Ali, M. Z., Yousafzai, H. U. K., Rehman, K. U., Shah, J. A., and Shiekh, N. A.: Smart Groundwater Monitoring System for Managed Aquifer Recharge Based on Enabled Real-Time Internet of Things, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-12909, <https://doi.org/10.5194/egusphere-egu23-12909>, 2023.
- Jayakody, P. M. (2015). The Influence of La Nina on Sri Lanka Rainfall. *Sri Lanka Journal of Meteorology*, 1.
- Jeewanthi, P. W., Withanage, N. S., & Ariyaratne, K. W. D. T. (2021). Identification of changes in rainfall pattern in paddy growing areas in Sri Lanka: A case study in Anuradhapura district. *Journal of Agriculture and Value Addition*, 4(1). <https://doi.org/10.4038/java.v4i1.88>
- Jiang, D., Wang, J., Huang, Y., Zhou, K., Ding, X., & Fu, J. (2014). The Review of GRACE Data Applications in Terrestrial Hydrology Monitoring. *Advances in Meteorology*, 24. <https://doi.org/10.1155/2014/725131>
- Khatri, P., Gupta, K. K., & Gupta, R. K. (2020). A review of partial least squares modeling (PLSM) for water quality analysis. *Modeling Earth Systems and Environment*, 7(2), 703–714. <https://doi.org/10.1007/s40808-020-00995-4>



- Klemas, V., & Pieterse, A. (2015). Using Remote Sensing to Map and Monitor Water Resources in Arid and Semiarid Regions. In *Advances in Watershed Science and Assessment* (Vol. 33, pp. 33–60). Springer International. [https://doi.org/10.1007/9783319142128\\_2](https://doi.org/10.1007/9783319142128_2)
- Kolusu, S. R., Shamsudduha, M., Todd, M. C., Taylor, R. G., Seddon, D., Kashaigili, J. J., Ebrahim, G. Y., Cuthbert, M. O., Sorensen, J. P. R., Villholth, K. G., MacDonald, A. M., and MacLeod, D. A.: The El Niño event of 2015–2016: climate anomalies and their impact on groundwater resources in East and Southern Africa, *Hydrol. Earth Syst. Sci.*, 23, 1751–1762, <https://doi.org/10.5194/hess-23-1751-2019>, 2019.
- Lakshmi, V. (2016). Beyond GRACE: Using Satellite Data for Groundwater Investigations. *Groundwater*, 54. <https://doi.org/10.1111/gwat.12444>
- MARAPANA, M. B. M. R. D. H. B. (2017). *STATISTICAL DOWNSCALING OF GRACE DERIVED TERRESTRIAL WATER STORAGE (TWS) PRODUCT: CASE STUDY FOR SRI LANKA*. [BSc dissertation, Sabaragamuwa University of Sri Lanka].
- Mindrila, D., & Phoebe, M. (2021). *Scatterplots and Correlation*.
- NING, S., ISHIDAIRA, H., & WANG, J. (2014). STATISTICAL DOWNSCALING OF GRACE-DERIVED TERRESTRIAL WATER STORAGE USING SATELLITE AND GLDAS PRODUCTS. *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, 70(4), I\_133–I\_138. [https://doi.org/10.2208/jscejhe.70.i\\_133](https://doi.org/10.2208/jscejhe.70.i_133)
- Nwankwoala, H., Osayande, D., Nwosu, C., & Amunabo, U. (2022). Groundwater exploration using vertical electrical sounding techniques in parts of Etche Local Government Area of Rivers State, Nigeria. *Global Journal of Engineering and Technology Advances*, 11, 088–100. <https://doi.org/10.30574/gjeta.2022.11.1.0070>
- Ouma, Y. O., Aballa, D. O., Marinda, D. O., Tateishi, R., & Hahn, M. (2015). Use of GRACE time-variable data and GLDAS-LSM for estimating groundwater storage variability at small basin scales: a case study of the Nzoia River Basin. *International Journal of Remote Sensing*, 36(22), 5707–5736. <https://doi.org/10.1080/01431161.2015.1104743>
- Panabokke, C., & Perera, A. (2005). *GROUNDWATER RESOURCES OF SRI LANKA*.
- Pirouz, D. M. (2006). An Overview of Partial Least Squares. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.1631359>
- Rajapaksha, P., & Rajendran, M. (2022). Assessment of Groundwater Quality Status in Medawachchiya DS Division in Anuradhapura District, Sri Lanka. *International Journal of Progressive Sciences and Technologies*, 34, 258–267. <https://doi.org/10.52155/ijpsat.v34.1.4559>
- Sokolechuk, K., & Sokáč, M. (2022). Comparison of spatial interpolation methods of hydrological data on example of the Pripjat river basin (within Ukraine). *Acta Hydrologica Slovaca*, 23(2), 226–233. <https://doi.org/10.31577/ahs-2022-0023.02.0025>
- Springer, A., Lopez, T., Owor, M., Frappart, F., & Stieglitz, T. (2023). The Role of SpaceBased Observations for Groundwater Resource Monitoring over Africa. *Surveys in Geophysics*, 44. <https://doi.org/10.1007/s10712022097594>

Wu, W.-Y., Lo, M.-H., Wada, Y., Famiglietti, J. S., Reager, J. T., Yeh, P. J.-F. ., Ducharne, A., & Yang, Z.-L. (2020). Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nature Communications*, 11(1). <https://doi.org/10.1038/s41467-020-17581-y>