Investigating Groundwater Recharge Caused by Cyclone Events in Northern Australia

This thesis is presented in partial fulfilment of the requirements
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by

Eleanor Dodsworth

Supervisor:

Prof. Paul Tregoning

Research School of Earth Sciences
The Australian National University

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Declaration

This thesis is an account of research undertaken between February 2026 and October 2026 at The Research School of Earth Sciences, The Australian National University, Canberra, Australia. To the best of my knowledge, this thesis contains no material previously published or written by another person, except where due reference is made in the text and has not been submitted in whole or part for a degree in any university.

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Abstract

Globally fresh water supplies are being depleted at a higher than sustainable rate. In the face of increasing droughts from a warming climate and the loss of permanent water bodies due to anthropogenic interventions, groundwater is the future of fresh water supplies, especially in Australia. In the Cambrian Limestone Aquifer in the centre of the Northern Territory, groundwater is already a key water source, with ephemeral lakes and rivers bringing unreliable water supplies and little rainfall occurring outside of the wet season. The region's groundwater is also under threat from proposed water intensive farming projects, aiming to grow crops such as cotton and Artificial Intelligence data centres that use large volumes of water for cooling. However, recent cyclone activity in the region has brought large volumes of rainfall into the arid centre, replenishing the regions groundwater supplies. In late December 2022, cyclone Ellie passed over the region bringing ∼250 mm of rainfall to the region over the span of a week. This cyclone was then followed by two more; Lincoln and Megan in February and March 2024 respectively which brought a combined total of ∼575 mm of rainfall. The mass change caused by the rainfall was detected by the Gravity Recovery and Climate Experiment Follow On mission. This region of mass change is as high as 600 mm in certain areas and spans across 1,000 km in northern Australia, primarily located in the Barkly region of the Northern Territory. This expansive region of mass change was determined to have recharged the groundwater aquifers in the months following the cyclones. For Cyclone Ellie, there was an estimated groundwater storage change of ∼30 km^3 and for Cyclone's Lincoln and Megan there was an estimated groundwater storage change of ∼64 km^3. These volumes are very significant for such a dry region and have widespread implications for future water management policy and infrastructure.

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Chapter 1

Introduction

1.1 Background

It is often said that Australia is the land of droughts and flooding rains but nowhere is this truer than in the central Northern Territory. The Barkly region is marked by seasons of heavy rain and seasons where less than 1 mm of rain falls over the course of months. This regions sits on the cusp of two climate zones, the northern tropical savanna and the southern warm grasslands. This creates high climate variability across the region with the north more likely to experience a high volume of precipitation over a short period of time and the south to be drier but rarely in drought. However, with the changing climate, the typical wet and dry season behaviour has begun to shift. In the last four years, the region has experienced high rates of precipitation and a number of cyclones. Australian cyclones typically follow the coast of northern Queensland, Western Australia and the Northern Territory. However, three cyclones in December 2022, February 2024 and March 2024 travelled over 500 km inland, bringing higher than average rainfall into the normally dry centre of the Barkly region. Following each of these cyclones an abnormally high gravity signal (Figure 1.1) was detected by the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission.

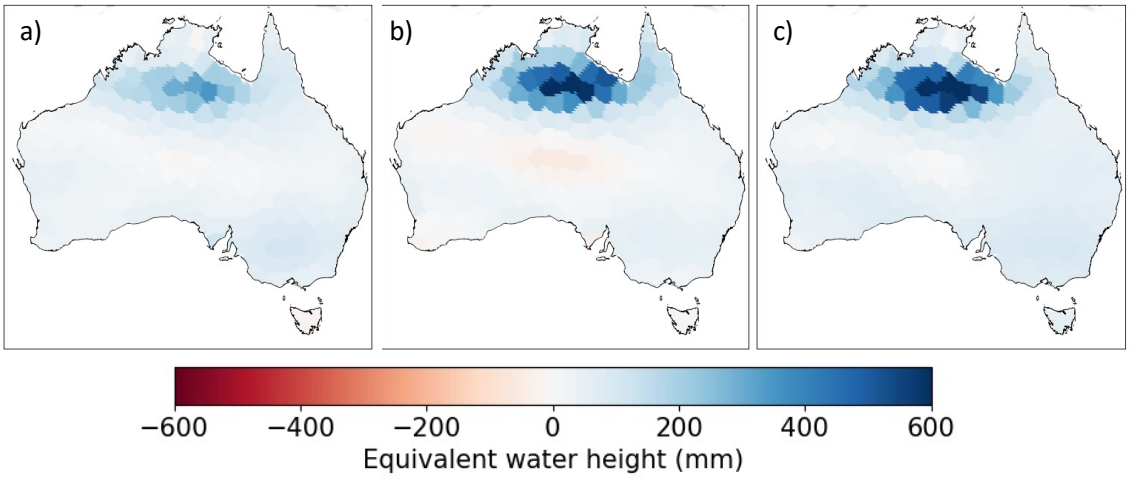


Figure 1.1: Mass estimate from GRACE-FO mission following the three cyclones a) Cyclone Ellie in January 2023, b) Cyclone Lincoln in February 2024 and c) Cyclone Megan in March 2024.

This abnormally high gravity signal, hereafter referred to as the 'wet blob', is an estimate of the region's total water storage (TWS), which is a combined total of all of Earth's layers where water can be found (surface water, soil moisture and groundwater). In the Barkly region, the TWS increased by over 400 mm after the first cyclone and 600 mm after the double cyclones in 2024. The TWS for the region typically increases by 100 mm over the course of a wet season. Hence, observing such a significant increase in the region in a short span of time raises questions about in which layers this water is currently located in and the implications for future water allocations and infrastructure developments. Hence, this project aims to evaluate the potential groundwater recharge events and how this water could be used to sustain future developments in the region.

1.2 Hydrology of Region

The wet blob as identified in Figure 1.1 spans across the mid Northern Territory and northern Western Australia. This region is classified as semi-arid and only receives significant rainfall during the 'wet season' from November to April each year. The rainfall is also highly variable, as can be seen in Figure 1.2, where there are periods of extreme rainfall and periods where less than 100 mm was recorded in a year. While the region is typically very dry, the Australian Bureau of Meteorology (BOM) has reported over the last 30 years it has experienced more annual rainfall on average (BOM and CSIRO, 2019),

with the last four wet seasons on average experiencing more rainfall. As shown in Figure 1.2, the wettest year recently was 2006 in which the region experienced a late season monsoon (BOM, 2006). The region also experiences a high rate of evapotranspiration during the wet season due to the warm temperatures and high volume of rainfall.

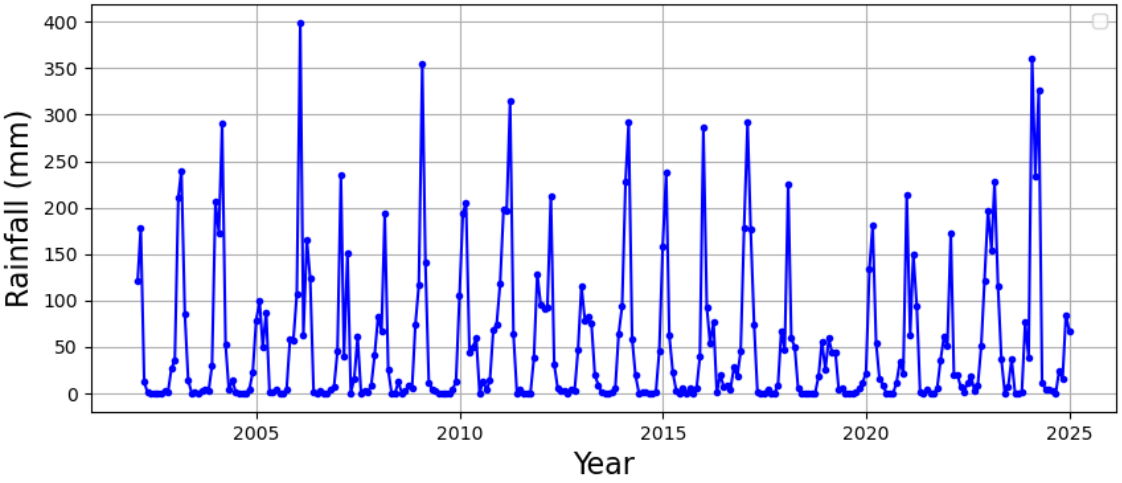


Figure 1.2: Monthly time series of rainfall in the wet blob region during the GRACE and GRACE-FO mission period (2002 - 2026).

The wet season also coincides with the Australian cyclone season. Cyclones in the Northern Territory typically follow the coast; however, during the time period (2002 – 2026) of the original Gravity Recovery and Climate Experiment (GRACE) mission and GRACE-FO (GRACE/-FO) there have been five cyclones that have passed through the inland region of interest in this study (Figure 1.3).

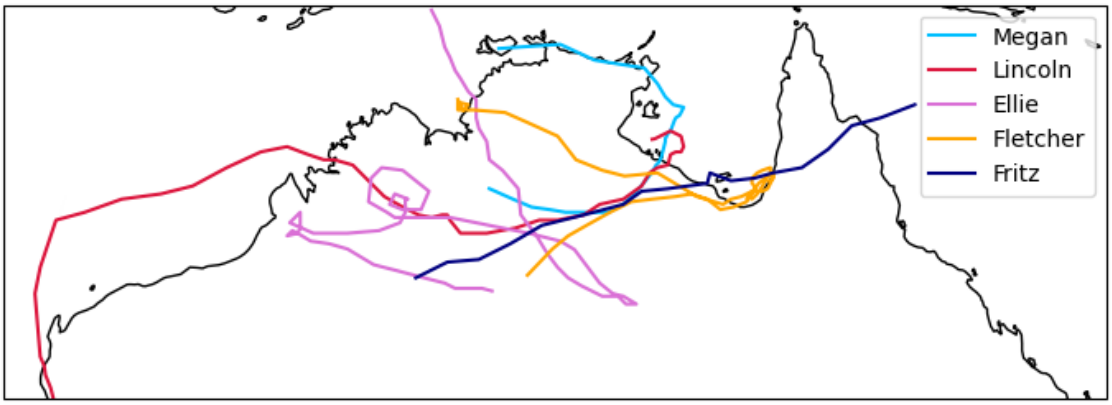


Figure 1.3: Cyclone paths for the five cyclones, Megan, Lincoln, Ellie, Fletcher and Fritz that have passed over the wet blob region during the GRACE/-FO period (2002 - 2026)

The first two Cyclones; Fritz and Fletcher, occurred in 2004 and 2014 respectively, and did not significantly increase the TWS of the region. In December 2022, Cyclone Ellie passed over the western half of the region and created the first occurrence of the wet blob. The TWS increased by 400 mm over the first few months of the year, with a small amount of drying occurring in the latter half of 2023. Cyclone Ellie caused widespread flooding, most notably in Northern WA along the Fitzroy River (Courtney and Paterson, 2023). The final two cyclones; Lincoln and Megan, occurred in February and March 2024. The two cyclones passed over the same coastal region in the Gulf of Carpentaria before diverging, with Lincoln continuing over the Indian Ocean and Megan dying down inland (Courtney, 2024a and Courtney, 2024b). This double cyclone event caused the greatest TWS increase in the region of any singular cyclone, with a three-monthly increase of 600 mm. While there was no cyclone during the 2024/2025 wet season, a tropical low and cyclone at the start of 2026 have continued to contribute to the GRACE-FO TWS and have sustained the wet blob to the present day.

1.3 Cambrian Limestone Aquifer

The region identified in Figure 1.1 lies primarily in the boundaries of one of Australia's largest groundwater systems; the Cambrian Limestone aquifer (CLA). This aquifer is approximately 100 – 300 m thick and is defined as a semi-confined to confined aquifer (Currell and Ndehedehe, 2021). The CLA is comprised of three sub basins, the Daly, Wiso and Georgina basins. The wet blob partially occurs over the Wiso and Georgina basins, which have a total storage volume of 740 km^3 (NTG, 2022). The annual groundwater recharge in the CLA is said to be between 22 mm/yr to 33 mm/yr (Crosbie and Rachakonda, 2021) when estimated using the chloride mass balance method, the most common method used for quantifying groundwater in Australia. The CLA has numerous groundwater discharge points within the aquifer, however the main one is Mataranka Springs in the Daley sub basin (Taylor et al., 2024). Groundwater from the Georgina basin flows northward toward these springs and helps maintain water levels year-round. The primary discharge point for the Wiso basin is the Flora River, on the border between Western Australia and the Northern Territory.

The region is home to two significant lakes, Lake Tarrabool and Lake Sylvester, both

of which are ephemeral lakes that fluctuate in size following rainfall events. Given their ephemeral nature, these lakes lose water to the CLA as they empty. Lake Sylvester is a series of three freshwater lakes that are interconnected by wetlands. When full the three sub lakes combine to create the larger Lake Sylvester. Following periods of high rainfall this lake can stay at its maximum size for over a year until it recedes back into its original state (de Caritat et al., 2019). Lake Tarrabool is similar in size and is also subject to seasonal rainfall variations. The lakes are critical water bodies, especially for migratory birds. For example, the Eva downs swamp, which is part of Lake Tarrabool is an international bird sanctuary that has been noted for its conservational significance (NTG, 2009).

1.4 Economic Significance

Although the Barkly region is extremely remote, the region has been at the centre of the Northern Territory Government's attention for some time. Recent changes in water licence legislation has opened up the region to more water-intensive irrigation and infrastructure projects. The most recent Georgina-Wiso water allocation plan (WAP) (2023 – 2031) has allocated 0.169 km^3 of groundwater out of the total estimated sustainable yield (ESY) of 0.210 km^3 for economic development (NTG, 2022). This allotment of water has been proposed for many different projects since the plan was released in 2023. The Larrimah farms project is one such example, which aims to grow water intensive crops such as cotton and melon around the town of Larrimah, to the north of the wet blob (NTG, 2025). This project requires approximately 0.0092 km^3 of water sourced from groundwater annually.

More recently, the Northern Territory Government has begun the planning process to build one of the country's largest artificial intelligence (AI) data centres just outside of Darwin. This plan highlights the potential for hyperscale computing that heavily relies on resources from the Barkly region. Principally, the centre requires water for cooling, water that has been proposed to be sourced from groundwater in the CLA. The predicted water usage for a data centre of this size is 0.0025 km^3/yr. The proposed data centres also relies on power generated from both renewable resources and non-renewable sources in the region. The first is the proposed SunCable project that aims to build a 12,000-hectare solar farm and battery near the town of Elliot (NTG, 2020). The other proposed energy

source is the Beetaloo sub basin, a shale gas field that lies below the CLA (Mouat and Garnham, 2026). After decades of debate, access to the gas field was finally granted in August 2026 and the pipeline between Darwin and Beetaloo is expected to be operational by the late 2020s.

1.5 Objectives

- Determine TWS change from cyclones with GRACE/-FO estimates.
- Understand if TWS caused groundwater recharge to occur and quantify the change in groundwater storage for the region, following each cyclone.
- Inform future water management and allocations for the region following recharge events.

1.6 Outline of Thesis

Chapter 1: Introductory chapter that provides details on the region of interest for this study; the Barkly region. The key section of this chapter introduce the hydrology and typical weather patterns for the Barkly region including past cyclone activity, the groundwater system that partially underlies the region and the economic significance of groundwater in the region.

Chapter 2: Review of current literature in the field of groundwater recharge quantification and satellite derived estimates of groundwater storage change. Also included is a review of methods such as available models and sensing techniques that can aid in detecting changes to groundwater.

Chapter 3: Study's methods, results and discussion presented from the paper *Cyclones recharge groundwater aquifers in the Northern Territory, Australia* (Dodsworth and Tregoning, 2026) written as part of this thesis project.

Chapter 4: Discussion of implications of results on future water management in the Barkly region, limitations of the study and future direction in which the study's results could be utilised for further research. The final section contains the conclusions of this study.

Chapter 5: Reflection on research and evaluation of skills, ideas and perspectives developed through the course of the thesis project and Masters program.

Chapter 2

Literature Review

2.1 Rainfall and Evapotranspiration

2.1.1 Rainfall Measurements

An integral component to quantifying cyclonic groundwater recharge is to first quantify the rainfall that occurred both during these cyclones and also generally in the wet season. Rainfall is typically measured using rain gauge data which is then interpolated to fill in the gaps between stations or through reanalysis data. There are many global rainfall products, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) model, which contains long-term (1950 – present) global precipitation information (Muñoz Sabater, 2019). While these types of models are very useful for long term analysis, they lack the resolution to accurately capture localised rainfall events, especially in the tropics (Lavers et al., 2022).

Interpolated rainfall datasets that rely on historical in situ measurements are more likely to accurately observe localised rainfall events for small precipitation events (>20mm) but may struggle with extreme precipitation events (Contractor et al., 2015). In Australia, interpolated rainfall data is available for the majority of the country from 1911 to yesterday on a 0.05° grid (Jones et al., 2009). This rainfall data is used in the Bureau of Meteorology's Australian Water Resources Assessment Landscape model v7 (AWRA-L) which is also estimated on a 0.05° grid (Frost et al., 2021). AWRA-L has daily measurements of rainfall and contains modelled measurements for evapotranspiration, soil moisture at three separate depths and surface runoff. As the rainfall data is measured using interpolation, the model relies heavily on having sufficient spatial coverage in order to accurately measure the rainfall. While this is achievable in high density population centres, for remote regions such as the central Northern Territory, the location of the Barkly region, the

spatial coverage is not always sufficient (Renzullo et al., 2011). There have been proposals to introduce satellite measurements into the interpolation, however Chappell et al. (2013) found that the addition of satellite data into the rainfall interpolation did not improve the overall accuracy and required additional work that was not necessary. It was noted, however, that including the satellite measurements would only be useful for extremely rural and remote locations such as central Australia.

2.1.2 Evapotranspiration Measurements

Another key component for measuring hydrological processes in northern Australia is evapotranspiration (ET). The ET in northern Australia is some of the highest in the country due to the very hot and wet conditions during the wet season (Zhang et al., 2025). Despite its importance, ET is difficult to measure accurately on a regional scale (Yi et al., 2024). Typically, models are used that have inputs from remotely sensed ET components such as thermal infrared and vegetation indices such as NDVI or from measurements taken from eddy covariance flux towers (Stoy et al., 2019). Flux tower measurements, which were used to calibrate the AWRA-L ET model, measure the covariance between latent heat and heat flux from the surface (van Dijk., 2010). This represents the flux of water from the surface due to ET processes (Isaac et al., 2017). While flux towers are the standard for measuring ET and are highly accurate, the spatial coverage of available flux tower measurements, is extremely limited, especially in Australia. The OzFlux network established in 2002 only contains 30 flux towers for the entirety of Australia, with one in each climate zone denoted by the Köppen-Geiger classification (Beringer et al. 2016). Therefore, flux tower measurements alone are not sufficient to accurately quantify ET in the region of interest.

Another option is to use modelled values. The AWRA-L model contains multiple ET datasets, including the modelled potential ET (PET), which is an estimate the upper limit on how much ET could occur at any location and the modelled actual ET (AET) which is an estimate of how much ET did occur (Zhang et al., 2025). PET is typically used in the measurement of AET but is not helpful in quantifying ET. The components that make up the AWRA-L modelled AET are the ET from the surface, soil moisture and groundwater:

$$AET = E_i + E_s + E_g + U_s + U_d + Y \tag{2.1}$$

Where E_i ,E_s,E_g are the evaporation from interception, soil and groundwater respectively. U_s and U_d are the transpiration from shallow and deep root water uptake and Y is the transpiration from groundwater (Frost et. al., 2021).

An example of the interpolated rainfall and modelled AET from the AWRA-L model can be seen in Figure 2.1 for the 20th of March 2024, during Cyclone Megan.

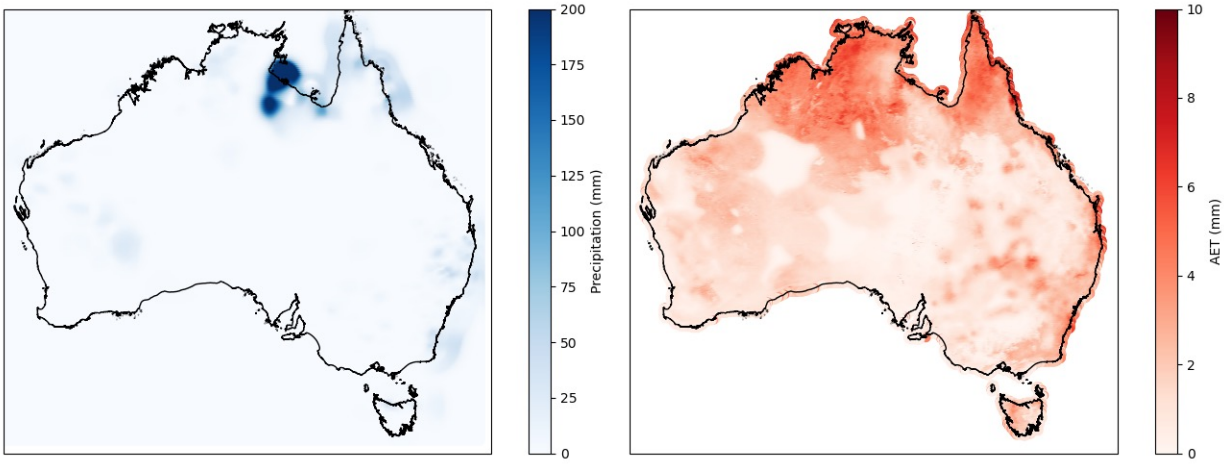


Figure 2.1: Example of interpolated rainfall data from Jones et al.(2009) on a 0.05°grid (left) and modelled AET from AWRA-L model on the same 0.05°grid (right) for March 20th 2024.

There are also models that combine remotely sensed measurements from sources such as MODIS, Landsat and Sentinel-2 (Guerschman et al., 2009). Many studies of the CLA have quantified ET rates using the CSIRO MODIS reflectance-based scaling evapotranspiration (CRMSET) algorithm (eg. Crosbie and Rachakonda, 2021; Crosbie et al., 2026a). This model estimates the AET at a 30 m resolution in monthly solutions. Prior to 2022, the CRMSET model was only integrated using measurements from MODIS, however the most recently available CRMSET v2.2 uses four different remote sensing missions to measure AET, these being Landsat, Sentinel-2, MODIS and VIIRS (Guerschman et al., 2022). The additional missions improve the model's estimates in both resolution (1 km to 30 m) and in frequency (monthly to daily). However, the publicly available data from McVicar et al. (2022) is only available as monthly solution with a measurement available in mm/day on the 1st of every month.

2.2 Soil Moisture Measurements

As well as groundwater, quantifying the soil moisture (SM) content is crucial to understanding where the water from TWS is currently located. There are many different methods that can be used to measure SM, including modelling, in-situ measurements and satellite derived measurements. The most commonly used is modelling, much like rainfall modelling, these datasets can be available on global or local scales. One such model is the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004). This is one of the most commonly used models to quantify soil moisture as it provides a global estimate. There are multiple different versions of the GLDAS model available, the only difference between them is in structure and source of forcing data. The three primary models of GLDAS are the Noah land surface model (LSM), variable infiltration capacity (VIC) LSM and the Catchment LSM (CLSM). The Noah LSM is the only model to have defined soil layer depths from 0 – 10 cm up to 100 – 200 cm. The soil moisture layers in the VIC and CLSM models have spatially variable depths but both contain a surface component between 0 – 10cm (VIC) and 0 – 2cm (CLSM). The GLDAS models are also assimilated with GRACE/-FO data from the Centre for Space Research (CSR) (Li et al., 2019). For the CLSM the GRACE/-FO TWS is also used to calculate the groundwater storage component as shown in Equation 2.2:

$$GW_{CLSM} = TWS - (SM_{Root\ Zone} + Snow\ Water\ Equivalent + Canopy\ intercept) \quad (2.2)$$

For the wet blob region, the layers of soil moisture as defined in the GLDAS CLSM model are shown in Figure 2.2 as an example of the GLDAS results.

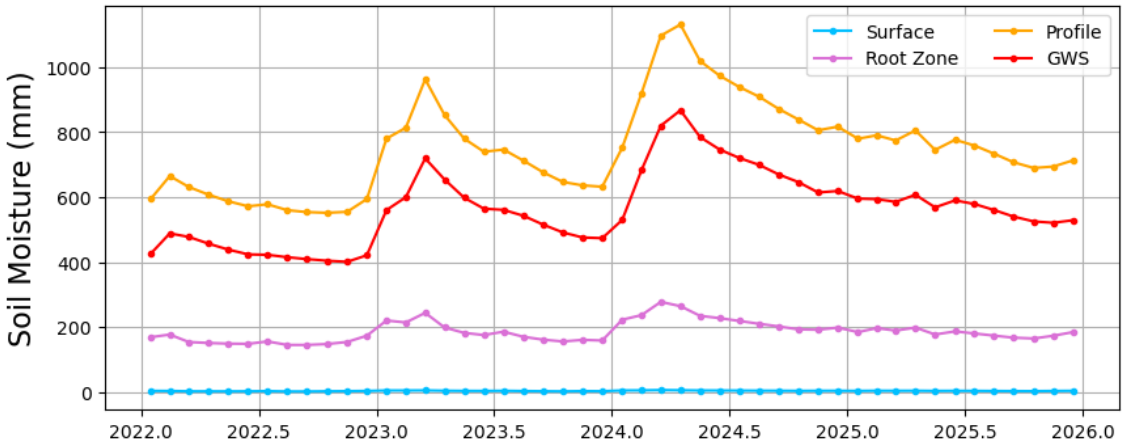


Figure 2.2: Monthly time series of wet blob region's soil moisture layers as defined in the GLDAS CLSM product, where the Surface represents the first two centimetres of soil (0 - 2 cm), Root Zone represents the first ten centimetres (0 - 10 cm), Profile contains the Surface and Root Zone measurements but has variable depths dependent on location and Ground Water Storage change (GWS) is also at variable depths below the Profile layer and is calculated with Equation 2.2.

Another method for quantifying SM is to use satellite data that can measure indirect components such as soil temperature, wind and precipitation. These satellites include passive, active and combined microwave satellites. A combination of all three are used in the European Space Agency's Climate Change Initiative for Soil Moisture (ESA CCI SM) (REF). The ESA CCI SM is a combination of radiometer and scatterometry data from various satellites with daily data available from 1978 to 31 December 2024. The dataset has used 5 active and 12 passive sensors over its lifetime and provides an active, passive or combined dataset. Some of the key sensors used in the most recently available dataset are the Soil Moisture Ocean Salinity (SMOS), Soil Moisture Active Passive (SMAP) and the Advanced Scatterometer (ASCAT). SMOS and SMAP both use L-band microwave radiation to measure the brightness temperature of the upper layers of soil (Kerr et al., 2010 and Piepmeier et al., 2017), whereas ASCAT uses C-band microwave radar to measure the soil wetness as a percentage of saturation in the upper layers of soil (Naemi et al., 2009).

2.3 Groundwater Quantification in Australia

Accurately measuring groundwater levels, flow and recharge is a difficult and often contentious task that can be achieved with many different methods (de Vries and Sim-

mers, 2002). In Australia, the most commonly used method for quantifying groundwater recharge is called the chloride mass balance (CMB) method which measures the concentration of chloride in groundwater samples. This method assumes that the chloride ion is a conservative tracer that comes solely from rainfall. By measuring the concentration of chloride in a groundwater sample the age and hence the aquifers retention time can be measured (REF). The CMB method assumes that groundwater is entering the system through diffuse recharge and occurs over a 1000-year period in arid environments (Scanlon et al., 2002). There have been numerous studies that utilise the CMB method in Australia, with some focusing on specific regions (e.g. Crosbie et al., 2022) and some creating continental scale maps (Lee et al., 2024). Crosbie and Rachakonda (2021) found that the recharge rate in the CLA was between 22 mm/yr and 33 mm/yr. The recent creation of an Australia wide diffuse recharge map places the rate between approximately 50 mm/yr in the northern region of the aquifer and below 10 mm/yr in the aquifer's southern region (Lee et al., 2024).

However, the results from the CMB method may be an oversimplification of the groundwater recharge systems, especially in northern Australia, because the CMB method makes several assumptions that may not fully reflect the processes occurring in northern Australia. The primary assumption made in measurements from CMB is that groundwater is being recharged through diffuse recharge, which is the absorption of groundwater evenly across a wide area. However, for arid and semi-arid regions groundwater recharge typically occurs through focused recharge, not diffuse recharge (Scanlon et al., 2006). This mechanism assumes that recharge is not occurring evenly across an area, instead occurring through fractures in rocks and sink holes (Lee et al., 2025). CMB also does not account for recharge that occurs via interactions between surface water and groundwater (Crosbie et al., 2022). Therefore, recharge occurring from the region's large ephemeral lakes is not being accounted for in this method. Finally, the CMB method quantifies recharge occurring over thousands of years in arid regions, but recharge has been shown to occur in shallower aquifers over shorter time periods. In some cave systems in southeastern Australia and northern New South Wales the groundwater recharge has been recorded just days after significant rainfall events (Baker et al., 2024 and Priestley et al., 2025). Closer to the study region, recharge through ephemeral rivers in the Ti Tree basin in central Australia

has also been recorded in the months following significant flow events caused by rainfall (Villeneuve et al., 2015).

The volume of water entering an aquifer though mechanisms such as rainfall or stream flow also plays an important role in groundwater recharge occurring. In the Ti Tree basin, located south of the wet blob, the minimum daily rainfall volume required for recharge to occur is between 150 – 200 mm (Boas and Mallants, 2022). Controlled testing and numerical modelling in South Australia has also shown the minimum required flow rate for ephemeral rivers in order for recharge to occur (Batlle-Aguilar and Cook, 2012). They found that for dry water bodies recharge only occurs following 15 days of flow. For water bodies that already contain higher moisture content, flow is only required to last for 10 days before recharge occurs. However, in northern Australia where the ET rates are higher, the ephemeral rivers require more days of flow to ensure the water retained at the surface will not be entirely lost to ET (Villeneuve et al., 2015).

2.4 GRACE and GRACE/-FO Mission

Gravity Recovery and Climate Experiment (GRACE) and its follow on (GRACE-FO) are satellite missions that detects changes in the Earth's temporal gravity field. The missions are comprised of twin satellites, separated by ∼220 km, operating in a near-polar orbit at an altitude of ∼490 km above the Earth. The satellites have a repeat time of 30 days and have a spatial resolution of 300 km. The GRACE mission was launched in 2002 and was active until 2017. It was then replaced by the GRACE-FO mission, launched in 2018 which is still operational. The next generation of gravity satellites, that includes the GRACE-Continuity mission, are due to form the Mass-Change and Geosciences International Constellation (MAGIC) which will increase the accuracy and repeat time of gravity measurements (Pfeffer et al., 2026).

Changes in the Earth's gravity field are detected from change in the distance between the two satellites. The distance between the two satellites varies when passing over significant gravity signals due to the gravitational pull acting on the satellites, and is measured through the use of the Microwave Instrument (MWI) on the GRACE mission and the MWI and Laser Ranging Instrument (LRI) on the GRACE-FO mission (Landerer et al., 2020). The MWI sends microwave signals between the two satellites, transmitted at two

frequencies one in the K-band (24 GHz) and one in the Ka-band (32 GHz) (Kornfield et al., 2019). On the GRACE-FO mission the LRI was included as a demonstration for a new method of measuring the inter-satellite distance. The LRI is operated by one satellite acting as the 'master' sending out the laser beam and the other acting as the transponder who receives the laser beam then sends it back to the first satellite (Sheard et al., 2012). The time taken for the laser to transmit between the satellite measures their distance from one another. The LRI was successful aboard the GRACE-FO satellites however, due to issues with fuel leakages, the satellites entered 'wide pointing mode' which allows the satellites to have relaxed pointing offsets of $\pm 2^{\circ}$. This wider pointing offset is too large for the LRI to accurately measure distance, and it was subsequently switched off in July 2023, distance is now only measured using the MWI (Landerer et al., 2026).

The gravity changes are directly inferred from the intersatellite distance and are then used to estimate mass change in that region. When a satellite passes over a region with strong gravitational potential the satellites experience an acceleration at separate times, the difference in their range when one is accelerating is directly proportional to mass attraction (Tapley et al., 2019). The temporal gravity field which represents the mass change is estimated from a least squares inversion . In some solutions this process is completed using the range rate (RR) which is the derivative of the intersatellite range with respect to time, while others use the range acceleration (RA), the double derivative of the intersatellite range (Figure 2.3).

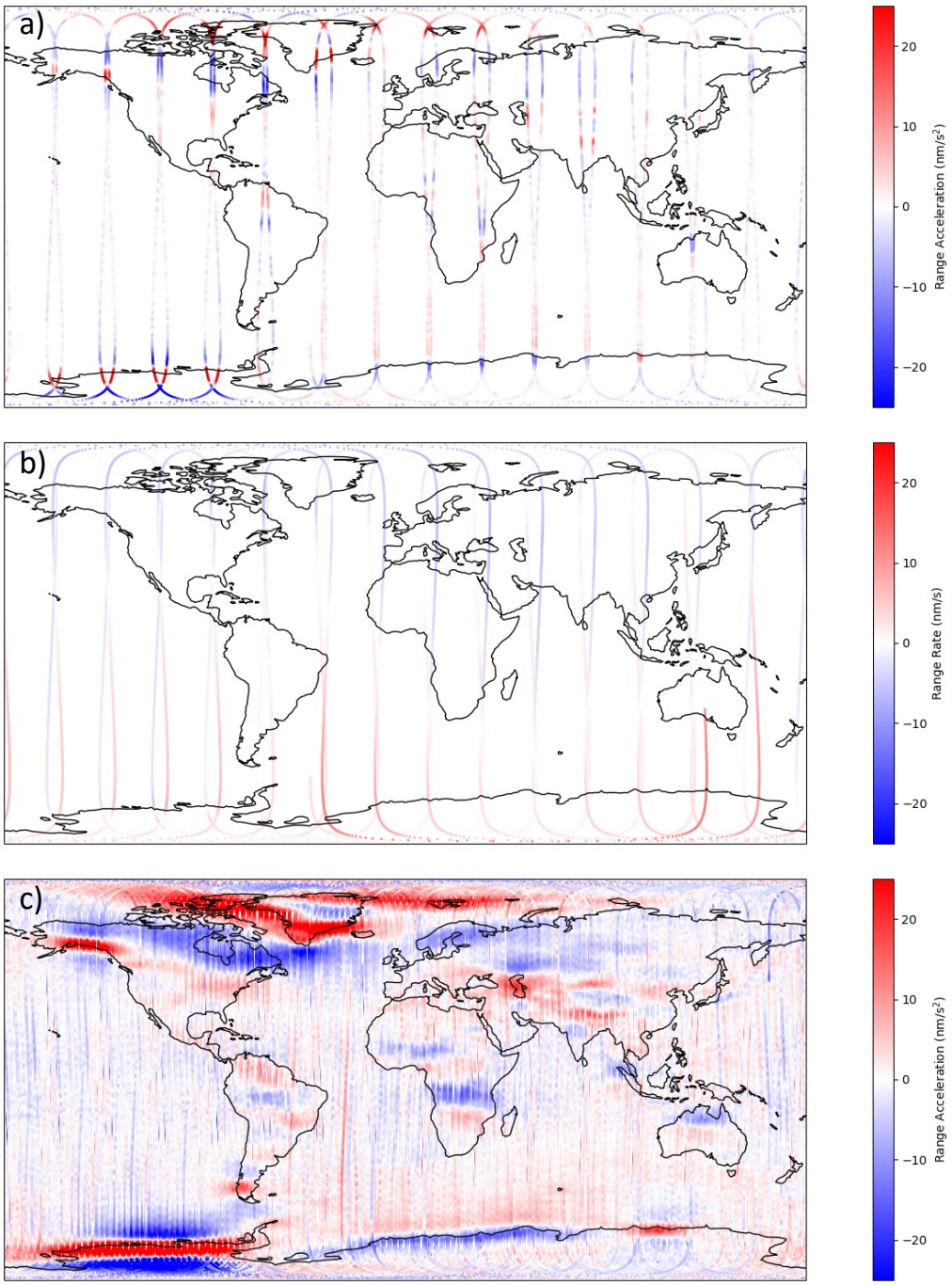


Figure 2.3: Example of a) range rate and b) range acceleration for a singular day (18th March 2024). Compared to c) monthly RA solution for March 2024

Typically mass change solutions calculated using RR or RA contain an error known as north south striping, where regions contain solutions that are unrealistic. This error can be reduced by applying regularisation to the mass change estimate (e.g. Save et al., 2012). An example of this is shown in Figure 2.4 where the left has 1/10th of the regularisation applied as the right.

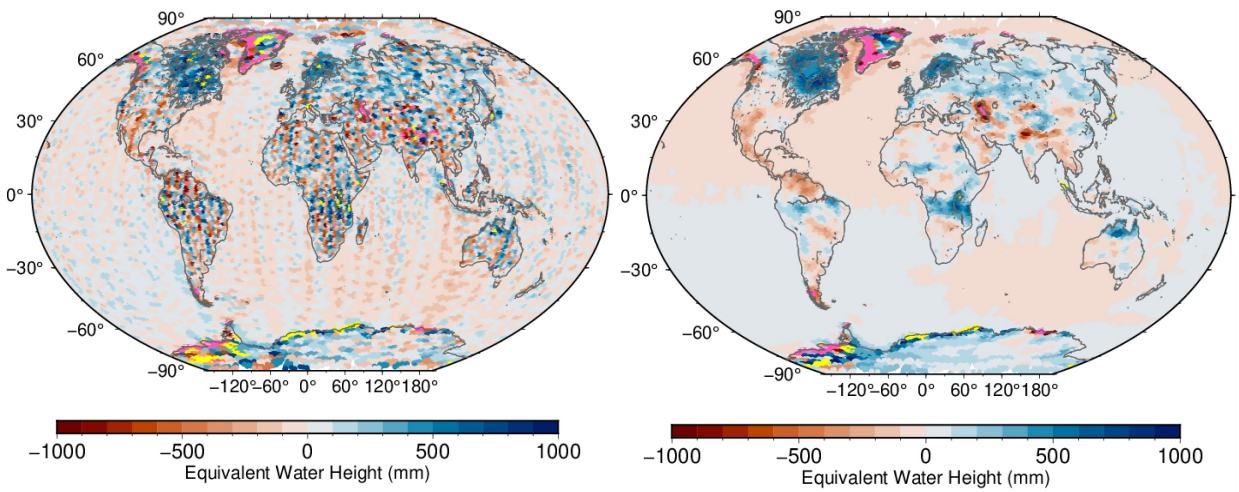


Figure 2.4: Example of north-south striping present in a RA estimate for March 2024, where left is the unregularised striped estimate and right is the regularised estimate

2.4.1 Total Water Storage

From the measured gravity signal, the change in total water storage (TWS) can be estimated. The TWS is the sum of all layers of the water cycle: snow, surface water, soil moisture and groundwater aquifers. The RR/RA results from the satellite are used to estimate water loss or gain due to the relationship between water and mass. When a region experiences a change in water, the mass of that region changes as defined in Newton's law of Gravitation. From the change in mass, the TWS can be estimated using spherical harmonics or a change in height on regions known as mass concentration elements (mascons). TWS estimated using the spherical harmonics method uses the spherical harmonic coefficients C_{lm} and S_{lm}, defined in Equation 2.3 to calculate mass change for any given location (Wahr et al., 1998).

$$N(\theta,\phi) = a\sum_{l=0}^{\infty}\sum_{ln=0}^{l}\tilde{P_{lm}}cos(\theta)(C_{lm}cos(m\phi) + S_{lm}sin(m\phi)) \tag{2.3}$$

Where a us the radius of Earth, θ and ϕ are colatitude and east longitude respectively, C_{lm} and S_{lm} are the spherical harmonic coefficients, and the $\tilde{P_{lm}}$ is the associated normalised Legendre function.

For mascons, the change in water height is estimated on a predetermined tile of a known area which is then multiplied by the density of water and mass change estimated by GRACE/-FO. TWS represented using mascons varies in shape and size depending on the source of the solution. The Centre for Space Research (CSR; Save et al., 2016) and Goddard Space Flight Centre (GSFC; Loomis et. al., 2019) both use 100 km $\times$ 100 km mascons on which they estimate TWS changes, CSR estimates mascons on a geodesic grid, while GSFC estimates mascons on equal-area cells. The Jet Propulsion Lab (JPL; Watkins et al., 2015) uses mascons tha are 300 km $\times$ 300 km spherical caps over an elliptical Earth surface and the Australian National University (ANU; Dodsworth and Tregoning, 2026) uses 200 km $\times$ 200 km mascons. There is also the COM-TG solution, which is a combination of the four solutions previously mentioned (McGirr and Tregoning, 2026). This solution weights the coarser solutions from ANU and JPL higher in order to preserve large scale signals whilst still containing smaller scale changes in the mascon solutions. The five different solutions are all shown in Figure 2.5 for February 2024.

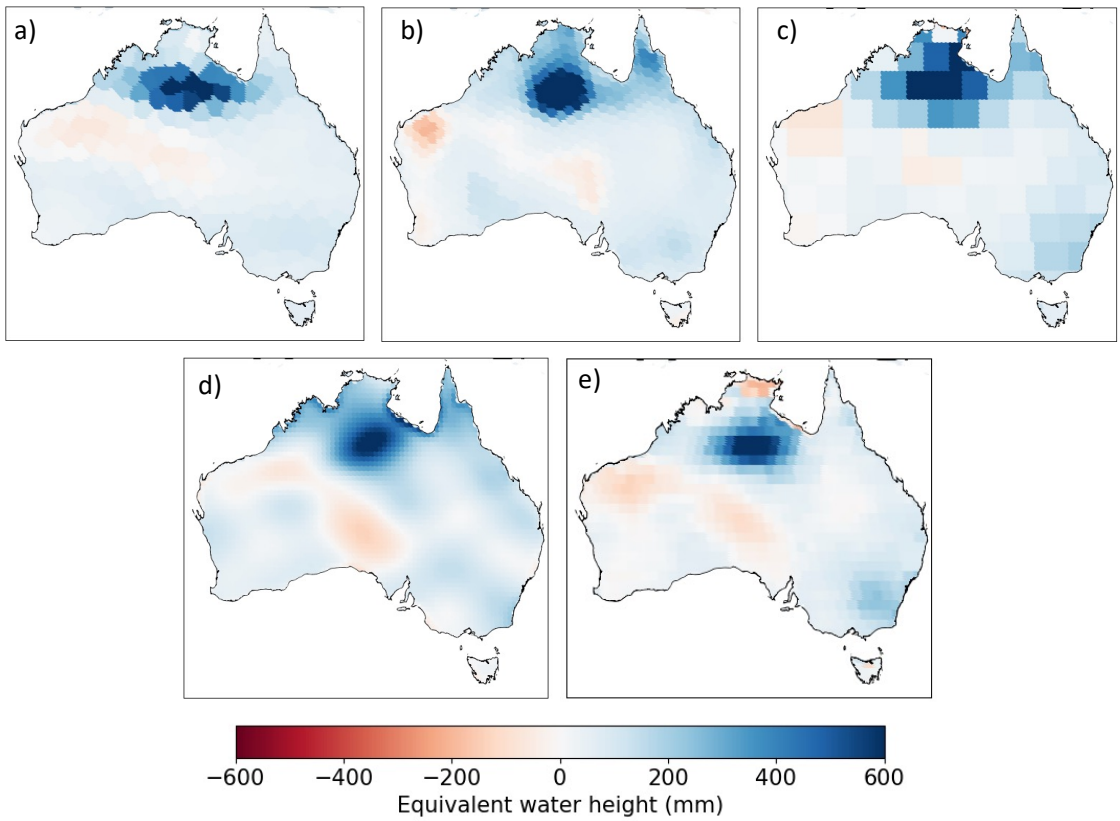


Figure 2.5: Example of mascon solutions from a) ANU, b) CSR, c) JPL, d) GSFC and e) COMTG for February 2024

TWS can be used to estimate any mass change that occurs in the components of the water cycle. It is commonly used to estimate the surface mass balance of polar ice sheets and sea level variations. Over the course of the GRACE/-FO missions' lifetime, the worlds ice sheets and glaciers have melted at an increasing rate. Despite monitoring of ice sheet changes prior to the GRACE/-FO missions, the mass change observed by GRACE/-FO TWS is the only direct estimate of ice mass change available on a continental scale (e.g. Velicogna and Wahr, 2005 and Tapley et al., 2019). Thus, making it an extremely valuable tool for understanding the current and future impact of a warming climate. Similarly, GRACE/-FO TWS can be used to estimate Ocean mass change, one of the key components in measuring sea level change (e.g. Chambers et al., 2004). This again highlights GRACE/-FO TWS's importance for understanding Earth's changes under a warming climate.

GRACE/-FO TWS estimates have also been used to quantify hydrological changes. In conjunction with other models and in situ measurements, changes in surface water,

soil moisture and groundwater can be derived from TWS changes (Rodell and Reager, 2023). These observations have been on continental and/or basin wide scales to observe changes in water storage either due to interannual variations or due to extreme climate events such as floods, droughts and cyclones (Rodell et al., 2018). GRACE/-FO TWS has been assimilated into land surface models (as mentioned in Section 2.2) and in monitoring programs such as the United States Drought Monitor (Houborg et al., 2012). Now that GRACE-/FO has been observing gravity change for over 20 years, these timeseries' are incredibly useful for understanding interannual change in water storage around the world. Prior to the GRACE/-FO mission, TWS depletion in regions such as India and China was only known anecdotally (Rodell et al., 2018). With the commencement of GRACE and it's follow-on, these trends were observed for the first time, allowing for depletion to be quantified and effort be made to reverse the effects (Famiglietti, 2014). Similarly, during the millennium drought in Australia TWS was used to observe the most drought affected regions, especially in the Murray-Darling Basin (Leblanc et al., 2012). TWS has recently been used to observe groundwater recharge from cyclones in the Arabian Peninsula (Saleh et al., 2025). However, the monthly solutions available from GRACE/-FO limit its usefulness in understanding the immediate effects of these climate hazards and hence are typically only used to identify the affected regions rather than measure their direct impact.

Currently GRACE/-FO solutions are limited to the 30-day repeat time of the satellite. However, attempts have been made to create sub monthly solutions, these include daily solutions (Croteau et al., 2020), 5-day solutions (Save et al., 2020) and 21-day solutions (Sakumura et al., 2016). These sub monthly solutions have been successful to a certain extent but are marred by leakage errors which places mass change in the wrong location (Croteau et al., 2020). Another method for sub-monthly TWS estimates that has been used is the Line-of-Sight Gravity Difference (LGD). This method uses a transfer function to project the intersatellite gravity difference onto the line of sight (LOS) direction, the vector joining the centre of mass of the satellites (Ghobadi-Far et al., 2018). As the LGD measurements represent instantaneous gravity change, they can be used to estimate short term TWS change (Ghobadi-Far et al., 2022). TWS changes estimated using LGD been used to identify and quantify the TWS for short term events such as floods in

Eastern Australia (Han et al., 2021) and Ukraine (Yi et al., 2025), and hurricanes in North America (Li et al., 2025). However, there are issues regarding the along track nature of the LGD product. When using LGD for discrete event analysis, measurements are assumed to be only occurring directly below the satellite, however if gravity signals are large enough, they may not be included in the LGD measurement but are still impacting the satellites' measured range, hence underestimating TWS change for that specific region (Tang et al., 2026). While there are currently limitations to creating sub monthly solutions, regardless of method, future developments such the MAGIC mission will improve the temporal resolution of the solution and may lead to more accurate sub monthly solutions in the future.

2.5 Groundwater Detection using GRACE/-FO TWS

On basin wide scales, GRACE/-FO TWS can also be used to quantify groundwater storage change (GWS). The simplistic approach is to remove the upper water storage components (surface water (SW), soil moisture (SM) and snow water (snow)) from the TWS and be left with the change in groundwater component as shown in equation 2.4.

$$GWS = TWS - (\Delta SW + \Delta SM + \Delta Snow) \tag{2.4}$$

This method, also known as the water balance method, is the most commonly used. What differs between studies is how the upper components are quantified. On a basin scale, the soil moisture and surface water are typically estimated using models, remotely sensed measurements or in-situ measurements (e.g. Sewnson et al., 2006 and Frappart and Ramillien, 2018). This method has been used to measure GWS in regions around the world in global scale studies (e.g. J. Chen et al., 2015 and Lo et al., 2016) and basin scale studies such as in the Central Valley in California (e.g. Famiglietti et al., 2011, Thomas and Famiglietti, 2019 and Reager et al., 2026), the Songhua River basin in China (e.g. H. Chen et al., 2019) and river basins in India (e.g. Bhanja et al., 2016; Girotto et al., 2017).

In Australia, this approach has been applied to certain basins, however it is not the most commonly used method for quantifying groundwater. In northern Australia, GWS in the Great Artesian Basin (GAB) and the CLA have been measured using GRACE/-FO

TWS. The GAB is a critical source of groundwater in Australia, owing to it significant size and storage capacity, however it contains limited in situ measurements. Therefore, GRACE/-FO TWS measurements have been utilised by some to measure the trends in GWS change. Kaushik et al. (2021) used TWS to analyse the relationship between GWS and rainfall in the GAB. They found that rainfall was the primary driver behind GWS by correlating rainfall data with the TWS minus modelled soil moisture. Similarly, Yan et al. (2016) also used TWS to infer changes in the GWS of the basin but did not attempt to calculate the GWS from the TWS. More recently Castellazzi et al. (2024) used TWS to quantify the GWS in the GAB from 2002 – 2022 and compare the result to the GWS estimated from the groundwater budget approach. With both approaches they analysed the basin by splitting it into the four sub basins and found that the groundwater was mostly stable with a slight increase in the middle sub basin. There are minimal differences between the two methods they compared, however it was noted that the GWS estimated from GRACE/-FO TWS may be overestimated due to the inclusion of shallower aquifers that overlay the GAB in the TWS calculation, whereas the groundwater budget method does not account for flood recharge and therefore may underestimate groundwater recharge.

The CLA is also a significant groundwater aquifer in northern Australia, however it is not as large or as populated as the GAB. Typically, the CMB method is used to measure GWS in the CLA, but GRACE/-FO TWS has been used to track GW depletion across the aquifer. Ndehedehe et al. (2025) used a combination of Landsat data and GRACE/-FO TWS to measure GWS across the CLA from 1986 - 2022. From their analysis it appears the CLA has undergone a significant rate of drying from 2014 – 2022, with water storage deficits reaching 150 km^3 in 2021 and GWS decreasing by 3.88 km^3/yr. They linked this depletion to changes in water licence legislation and the following over-extraction of groundwater. However, in a comment made by Crosbie et al. (2026b), it was noted that the current groundwater extraction rate of 0.07km^3/yr could not cause a deficit of 150 km^3 and that groundwater-based irrigation commenced almost a decade prior to 2014. Crosbie et al. also called into question the validity of the in-situ borehole analysis shown in Ndehedehe et al. (2025) as they relied on only four clusters of bores, two of which are outside the CLA and all of which show changes driven by climate-dominated signal rather

than being driven by groundwater extraction. The time period of the study also does not include the three recent cyclones and, hence, does not comment on potential GWS in the CLA, which is likely to have occurred following these events.

The water balance method has also been used to estimate GWS in southeastern Australia, primarily the State of Victoria, which partially lies in the Murray Darling Basin. Chen et al (2016) used this approach to both quantify and to observe trends in GWS during the Millenium Drought from 2003 – 2012. They found that the estimated GWS and the in-situ boreholes largely agreed with one another, highlighting the importance of GRACE/-FO TWS for estimating GWS when boreholes are limited such as in the Northern Territory. Similarly, Leblanc et al. (2009) also observed the impacts of the Millenium Drought using GRACE TWS and borehole measurements and were able to estimate the volume for water lost throughout the drought period. More recently, Park et al. (2025) estimated GWS using the same approach with satellite-derived SM and again found a close relationship between the borehole measurements and the GWS from GRACE/-FO TWS.

The water balance method derived from GRACE/-FO TWS also estimates that groundwater is occuring much faster than the CMB method introduced in Section 2.3 . The CMB method assumes that recharge is averaged over thousands of years in arid environments (Crosbie et al., 2010). However, the water balance method assumes recharge can occur over much shorter time periods, from a few months to years. Studies in the Central Valley in California have been able to quantify annual groundwater recharge rates and establish the drivers behind that recharge (Argus et al., 2022; Reager et al., 2026). The recharge measured in the GAB and CLA by GRACE/-FO TWS is also on yearly timescales (Castellazzi et al., 2024; Ndehedehe et al., 2025) indicating that, despite the northern Australia being an arid environment, recharge can occur in shorter periods of time.

Chapter 3

Groundwater Recharge from Cyclones

While volumes of groundwater are often utilised to estimate the sustainable yield of an aquifer, they can be hard to estimate on a basin scale. Typically, point sources such as boreholes are used to measure the groundwater in a specific area and then used for interpolation. However, this interpolation may miss localised recharge events. In order to improve spatial resolution remote sensing methods such as the GRACE-FO mission can be used in conjunction with modelled values. Here GRACE-FO TWS, modelled data and in-situ measurement were used to estimate the volume of groundwater storage change (GWS) following each of the cyclones (Ellie, Lincoln and Megan) that have passed over the region in the last four years.

The work presented in this chapter is from the publication *Cyclones recharge groundwater aquifers in the Northern Territory, Australia* (Dodsworth and Tregoning, 2026) which was submitted to JGR: Earth and Space Science on October 4th 2026 and written as part of this thesis project. As this chapter was written in the form of a stand-alone paper, there is some repetition from Chapters 1 and 2; however, the majority is unique to this chapter and is a combination of the methods, results and discussion chapters.

3.1 Abstract

Groundwater is a critical resource for communities around Australia, especially in the remote and arid Barkly region of the Northern Territory. Recent legislation changes and technological developments have placed pressure on this region's critical groundwater, highlighting its importance for development and for sustaining existing lifestyles. Despite

the rising threat of groundwater depletion, the region has experienced record breaking wet seasons in the last four years and in late 2022 and early 2024 the region was impacted by three significant cyclones. These cyclones precipitated a large volumes of water onto the Earth's surface, which was detected by the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission as an increase of up to 600 mm of total water storage. This water increased signal spans over 1,000 km across northern Australia and has persisted since its first detection in January 2023. Here we find that Cyclone Ellie in late 2022 caused ∼30 km^3 of groundwater recharge and Cyclones Lincoln and Megan, which occurred less than a month apart in early 2024, caused ∼64 km^3 of groundwater recharge. The total water increase from these three cyclones still persists into mid 2026.

3.2 Plain Language Summary

Australia is an extremely dry continent that relies on water sourced from the ground, known as groundwater, in order to sustain year-round water supplies for many inland regions. Recent developments in both technology and law changes have increased the reliance on these scarce water sources, putting them at risk of serious depletion. However, there is hope for the once very dry centre. Over the last four years, Australia's northern region has experienced an increase in cyclones passing inland, rather than following the coast as they usually do. These cyclones caused a large volume of rain to fall inland, causing widespread flooding which was observed by satellites passing above. These satellites detected an increase in water over a region that spans over 1,000 km and has been consistently monitored for the last four years. Over this time, the water has travelled through the soil into the groundwater where it is now being stored in aquifers from where it can be extracted for use in the future. In this study we found that Cyclone Ellie in December 2022 increased the water in the aquifer by ∼30 km^3 and Cyclones Lincoln and Megan increased the aquifer's water by ∼64 km^3 in February and March 2024.

3.3 Introduction

Access to fresh water resources is becoming a critical issue faced by communities under threat from climate change. With depleted sources of surface water, these communities are

turning to groundwater to source their water (Taylor et al., 2012). This change in water source is putting pressure on groundwater aquifers, which could have dire effects in future decades (Doble et al., 2023). It is critical that these fragile aquifers be better monitored and the true extent of available water be understood in order to preserve groundwater as a viable and ongoing water source.

Australia's Northern Territory is a region highly dependent on groundwater as a source of fresh water. Groundwater is used for irrigation, agriculture, domestic use and cultural practices. However, recent changes in legislation have made gaining permission to access groundwater easier than ever. The Northern Territory Government has relaxed regulations opening the region to more intensive agricultural practices, such as cotton farming and has indicated an interest in building water-intensive Artificial Intelligence data centres in the region (Currell et al., 2024, Mouat and Garnham, 2026). This not only increases the stress on already low groundwater levels but also increases the strain on the local environments (Ndehedehe et al., 2025). Many of the lakes and rivers in the region rely on the groundwater from the Cambrian Limestone Aquifer (CLA) to sustain water levels year-round (de Caritat et al., 2019). These water bodies are critically important for migratory birds and are considered to have a high conservation significance in the Northern Territory (NTG. 2009).

The Northern Territory experiences a dry season during the Australian winter (April to October) and a wet season during the Australian Summer (October to April). In the region's arid centre, annual rainfall almost entirely occurs during the wet season. Some rainfall occurs in the dry season in the north of the region, but this is minimal (ie. <100 mm). The extreme rainfall in the wet season and minimal in the dry causes the region to have some of the largest range of rates of evapotranspiration (ET) in Australia (Zhang et al., 2025). The Australian cyclone season, which also occurs from December to March, further contributes to the extreme rainfall the region experiences.

The Northern Territory typically experiences 2-3 cyclones each year that mostly affect the northern coastline. Some cyclones travel into the centre of the Northern Territory, as far south as the town of Tennant Creek, but such cyclone events are very rare. It is projected that, under a warming climate, the cyclones in the Northern Territory will intensify and cause a greater volume of precipitation (CSIRO, 2024). Therefore, it can

be expected that the once arid climate of the central Northern Territory will become significantly wetter. This trend is already being observed in the Barkly region, where annual rainfall has risen by 14% in the last 30 years (CSIRO, 2019). This change in climate could greatly alter the land use in the region and open the region up to more water-intensive agriculture and irrigation.

Despite the rising threat of groundwater depletion, the region has received above average rainfall during the last four wet seasons. Starting in December 2022 when Cyclone Ellie occurred, a significant increase in total water storage (TWS) has become evident in analyses of data from the Gravity Recovery and Climate Experiment Follow On (GRACE-FO) mission (Figure 3.1b) (there is an anomalous cold region in the Northern Atlantic that is commonly called the 'cold blob' (Mooney, 2015); here we use similar language and call this region of increase in TWS the 'wet blob'). The water levels within the wet blob have continued to grow since the initial cyclone in 2022, primarily due to a further two cyclone events in the 2024 wet season (Figure 3.1a). These two cyclones, Lincoln and Megan, brought a combined total of $\sim$ 1500 mm of precipitation and caused widespread flooding in the region. In the two years since these cyclones, the TWS levels within the blob have remained high and show little sign of drying out. Given the typical scarcity of water in the region, has this water replenished the groundwater supplies and can it be useful for these proposed water-intensive projects?.

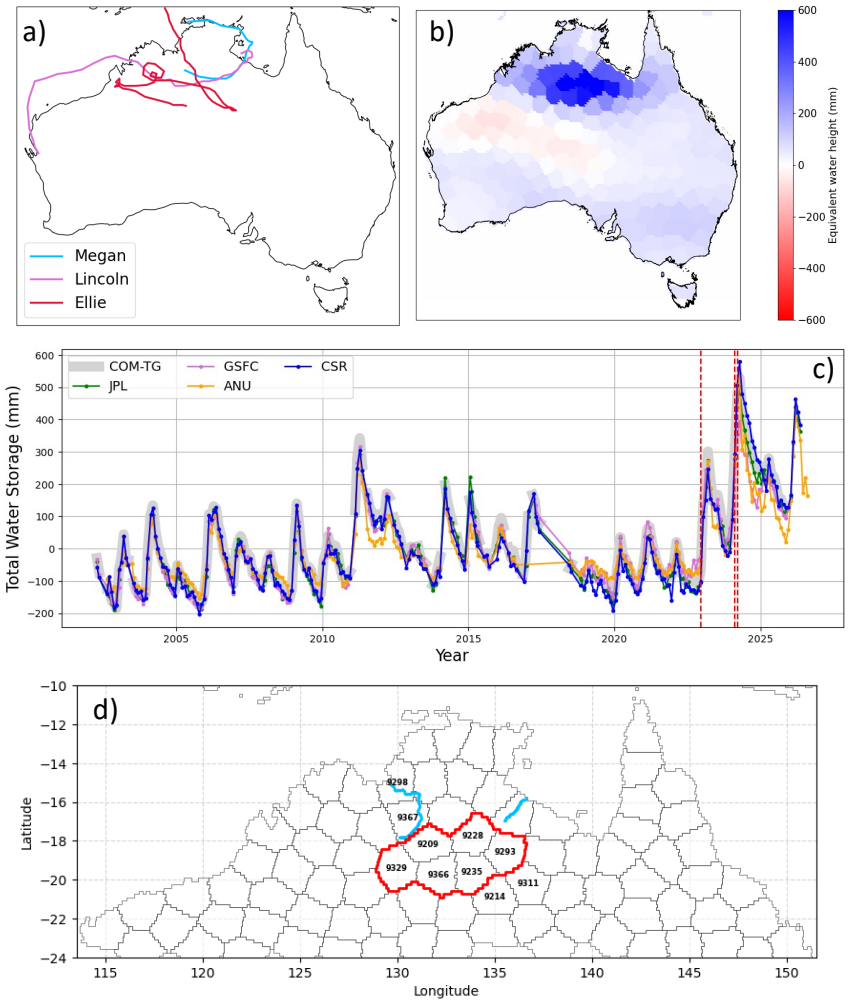


Figure 3.1: a) Cyclone paths of the three cyclones; Ellie, Lincoln and Megan, that pass through the region of interest in the GRACE/GRACE-FO period of 2002 - 2025. b) total water storage anomalies for the 'wet blob' mascons in March 2024, directly following the double cyclone event. c) Time series of integrated total water storage within the wet blob during the GRACE and GRACE-FO period. Mascon solutions of ANU, CSR, JPL and GSFC are shown, along with the COM-TG combined mascon solution (thick light grey line). The dates of the three cyclones are indicated with the dashed red lines. d) Identifying numbers for the ANU mascons discussed in this study. The perimeter of the wet blob is shown in red. Rivers used in this study are plotted (blue).

Very little is currently known about the mechanisms by which groundwater is recharged and how to quantify it (Lee et al., 2024). The most widely used method to estimate recharge in Australia is the chloride mass balance method (CMB) (Crosbie et al., 2010). Using this method, the rate of groundwater recharge in the CLA is said to be between 22 mm/yr and 31 mm/yr, and the process can take thousands of years following the initial rainfall (Crosbie et al., 2010 and Crosbie and Rachakonda, 2021). However, the use of models and controlled testing show the rate of recharge to be greater and to occur more rapidly (Lee et al., 2024, Priestley et al., 2025). Recently, Baker et al, (2025) tested groundwater recharge rates in Southeastern Australia by monitoring water percolation through cave systems and found that groundwater recharge can occur in the days following a significant rainfall event rather than the previously proposed longer timescales. Arid environments, such as the Barkly region, are also known for an increased rate in focused recharge (concentrated recharge through surface features), rather than diffuse recharge (uniform recharge through soil) (Scanlon et al., 2006). Focused recharge is known to occur at a faster rate than diffuse recharge (Lee et al., 2025), making it possible that groundwater recharge rates in the region are being misrepresented by the commonly used CMB rates which assume that diffuse recharge is occurring.

An alternative method for quantifying groundwater is to use the TWS from the GRACE and GRACE-FO missions (GRACE/-FO) and subtract the top layers of the water table. This method has been used across Australia, from the state of Victoria (Park et al., 2025) to the Great Artesian Basin in northern Australia (Castellazzi et al., 2024). These studies have shown that GRACE/-FO measurements closely align to available in situ measurements and could provide a highly accurate method for quantifying groundwater change in extremely remote regions that have little to no in situ measurements. Outside of Australia, GRACE/-FO data have also been used to quantify groundwater recharge from cyclonic activity in the Arabian Peninsula (Saleh et al., 2025). The GRACE/-FO data is typically used in conjunction with a land surface model, such as the Global Land and Data Assimilation System (GLDAS), in order to separate the satellite-based total water storage (TWS) estimate from GRACE/-FO into components of surface water, soil moisture and groundwater. However, Crosbie et al. (2026b) noted that the use of a single global land surface model is not sufficient to represent these water levels on a aquifer-wide scale.

Instead a multi-model approach should be taken and additional hydrological information is required.

In this study we explore a possible groundwater storage change caused by Cyclone Ellie in December 2022 and the two back-to-back cyclones (Lincoln and Megan) in early 2024. We first quantify the increase in TWS from the GRACE-FO satellite data. Next, we analyse the available hydrological data to isolate the upper layers of the water table. Finally, we determine the volume of groundwater recharge within the 'wet blob' in the years following the double cyclones and the implications for future water usage in the region.

3.4 Datasets

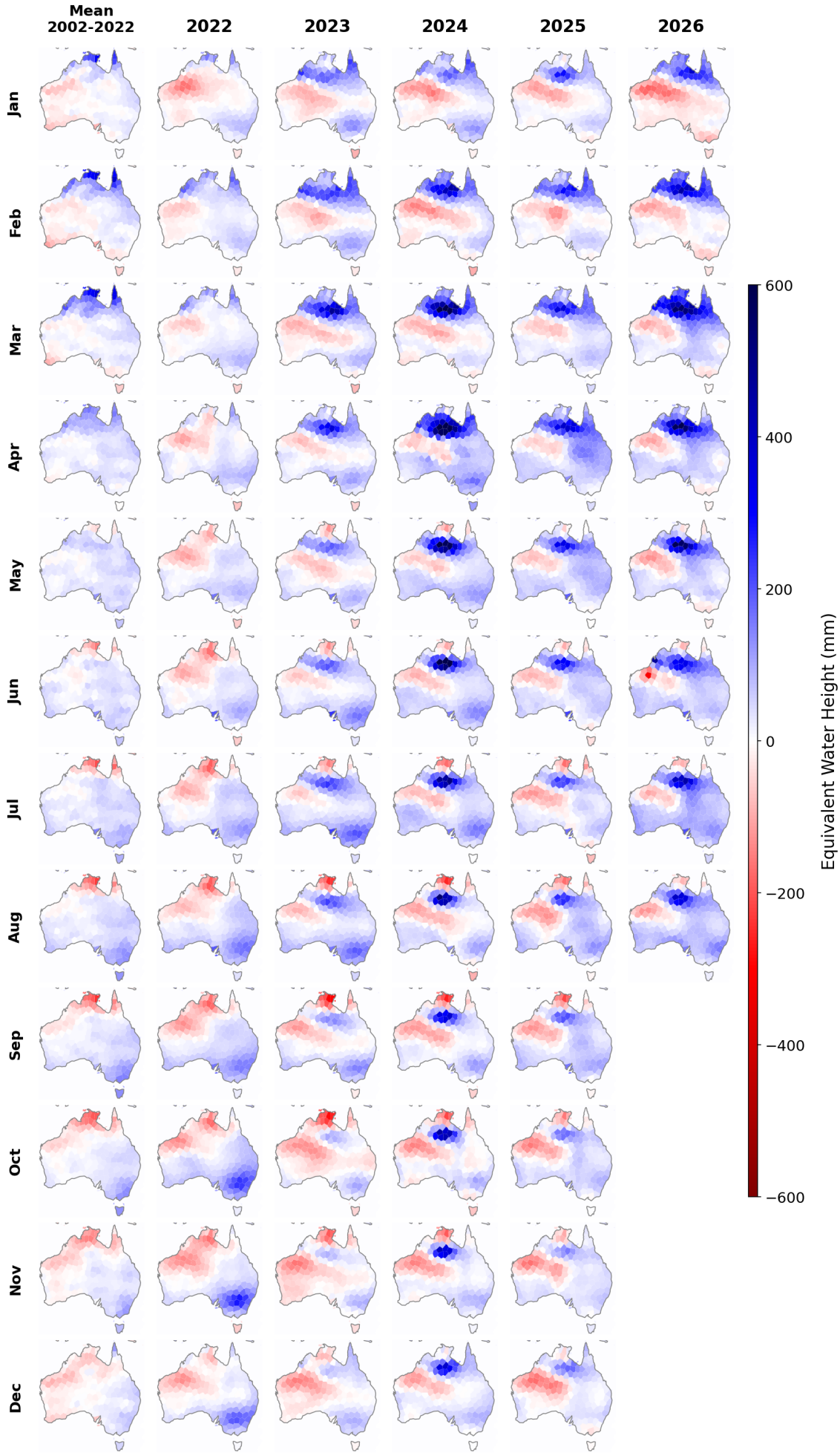
3.4.1 Cyclones

Data for the three cyclones investigated in this study were sourced from the Australian Tropical Cyclone Database, available through the Australian Bureau of Meteorology (BOM). The cyclone database provides the time and position (latitude and longitude) of all cyclones as they pass near and over Australia (Figure 3.1a). Additional information is also available from the database for Cyclones Ellie, Lincoln and Megan, including hourly rainfall totals and wind intensity.

3.4.2 Rainfall and ET

The rainfall and evapotranspiration (ET) datasets used in this study were sourced from the Australian Water Resources Assessment Landscape model version 7 (AWRA-L) (Frost et al., 2021). The AWRA-L model (van Dijk, 2010) is a distributed water balance model that simulates the flow of water through the system with water entering as precipitation and leaving through either ET, runoff or drainage into groundwater. The rainfall component is a record of historical daily station rainfall data that has been interpolated on a 0.05° grid (Jones et al., 2009). While for the majority of Australia there is sufficient coverage from rain gauge measurements for this interpolation to be highly accurate, it has been noted that, in extremely remote regions such as the central Northern Territory the rainfall data could be improved through the use of satellite data (Chappell et al., 2013). However, this

has not been implemented into the model. The ET model is the sum of evaporation and transpiration from upper soil layers and groundwater. We subtracted the ET from the rainfall and referred to this as *rain-ET*.


Mean
2002-2022
2022
2023
2024
2025
2026
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
600
400
200
0
−200
−400
−600
Equivalent Water Height (mm)

3.4.3 GRACE-FO Total Water Storage

The Gravity Recovery and Climate Experiment satellite mission (GRACE) measured the Earth's temporal gravity field from 2002 - 2017 and was succeeded by the GRACE Follow On (GRACE-FO) mission in 2018. For this study, GRACE-FO data were used to measure the changes in the Total Water Storage (TWS) which is a quantification of changes in the combination of Earth's water layers (surface, soil moisture and groundwater). The changes in Earth's gravity field are typically parameterised using spherical harmonics or through mass concentration (mascon) elements (e.g. Tapley et al., 2004 and Luthcke et al., 2006). In this study we used four different monthly mascon solutions: the Goddard Space Flight Centre (GSFC) (Loomis, Luthcke, & Sabaka, 2019), Centre for Space Research (CSR) (Save et al., 2016 and Save et al., 2020), both of which use 100 km $\times$ 100 km mascons, the Jet Propulsion Lab (JPL) (Watkins et al., 2015)solution which uses 300 km $\times$ 300 km mascons and the Australian National University (ANU) solution on 200 km $\times$ 200 km mascons. We also use the the COM-TG combined solution (McGirr and Tregoning, 2026) which is an average of these four solutions, provided on a 0.25° grid. The CSR, GSFC and JPL solutions all use the range rate for estimating mass change within the mascons. The ANU solution uses the range acceleration (RA) (the time derivative of the inter satellite range rate (Allgeyer et al., 2022) to estimate mass changes. All mascon solutions are a measure of the monthly TWS anomaly relative to the average of 2004 to 2010. GRACE/-FO TWS is commonly used to measure groundwater storage change across large aquifers and has been used to measure GW change in the CLA prior to the cyclones (Ndehedehe et al., 2025).

The spatial pattern of monthly TWS anomalies for mascons in Australia (2022 to 2026) are shown for the ANU mascon solutions (Figure 3.2), along with the mean monthly values from 2002-2021. The wet blob is not present in the 2002-2021 average solution nor in the 2022 TWS anomalies. Typically March and April have the highest TWS anomalies in northern Australia, but the blue shadow disappears by December. Ever since Cyclone Ellie, the higher than average TWS anomaly has consistently been present in each monthly estimate. After the double cyclones in 2024, the TWS anomalies became even more positive and have persisted - without weakening - since early 2024 to mid 2026.

3.4.4 GLDAS

We used the Groundwater and Soil Moisture Conditions from CLSM025 Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) V3.0 which includes assimilated GRACE/-FO data. This model was used to quantify the soil moisture (SM) component of TWS for this study. The GLDAS SM product contains three layers: the surface, Root Zone and Profile soil moisture. The surface layer is the water content in the first 2 cm (0 – 2 cm) of soil, the root zone contains the first 100 cm (0 - 100 cm) of soil and the profile layer contains the water content from 100 cm to a depth that varies spatially. The root zone soil moisture product was primarily used to better understand the water in the system prior to its movement into the shallow groundwater aquifers (Figure 3.3). While it has been shown that GLDAS is not the most accurate measure of SM in Australia (Park et al., 2025), other alternatives such as the European Space Agency's Climate Change Initiative for Soil Moisture (ESA CCI SM) product is not available for the entire time period of this study and, therefore, was not considered. The GLDAS model also provides an estimate for groundwater which uses the TWS and additional hydrological features:

$$GW_{GLDAS} = TWS - (SM_{RZ} + Snow\ Water\ Equivalent + Canopy\ interception) \quad (3.1)$$

Given that there is no snow and little river runoff in the region of the wet blob, the groundwater component of the GRACE-FO TWS estimates can be isolated by subtracting the monthly mean of the root zone soil moisture (Figure 3.3).

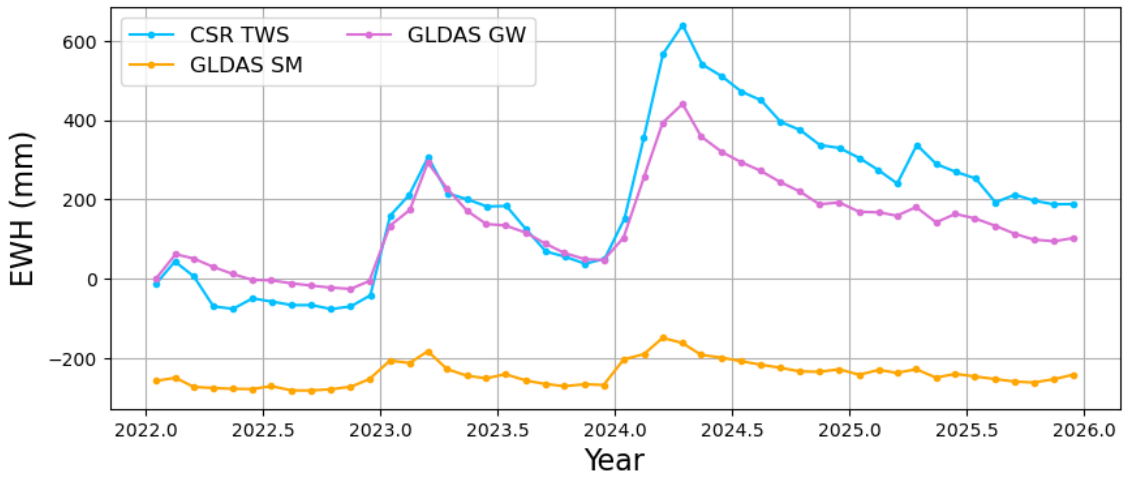


Figure 3.3: Time series showing the GLDAS groundwater layer, root zone soil moisture layer and the CSR GRACE-FO TWS anomalies, which is the GRACE/-FO solution assimilated into the GLDAS CLSM products. A mean of 2008 values was removed from the GLDAS products to compute SM anomalies in order to align with the GRACE-FO TWS anomalies (which are relative to the mean TWS of 2004 - 2010).

3.4.5 In-Situ Measurements

Groundwater bore and Northern Territory River gauge datasets were sourced from the Northern Territory water portal database and the BOM groundwater explorer database. There are very few active bores in the region. The majority of bores are concentrated in the eastern half of the wet blob due to the larger towns and proximity to the main highways (Figure 3.4). The lower left corner of the wet blob does not contain any borehole measurements. The bore depths range between 80 – 210 m and all have measurements that predate the first cyclone in 2022. The bore depth is critical to the understanding of the bore data as the bores may be sampling different layers of the aquifer, which can affect the measurement of changes in groundwater storage (Figure 3.5). In order to compare the measured depth below ground to water height, a porosity of 0.3 was assumed (the porosity values used in the GLDAS model) and multiplied by the change in depth to groundwater bore water depth measurement.

The river gauge measurements for the McArthur and Victoria Rivers were also obtained from the NT water portal. The gauge measurements also predate the cyclones, with measurements dating back to 1968, and quantify the stream discharge as well as river height. There are three river gauges on the McArthur River: at Baileys Grave, the McArthur River mine site and Borroloola crossing near the coast (Figure 3.4). There

is only one river gauge for the Victoria River that lies within the wet blob at Timber Creek. This gauge is located further upstream than the confluence of additional rivers such as the Baines River and Bullo River, meaning that the gauge does not measure the full extent of water leaving the surface into the ocean. No other river gauge data are available in the region.

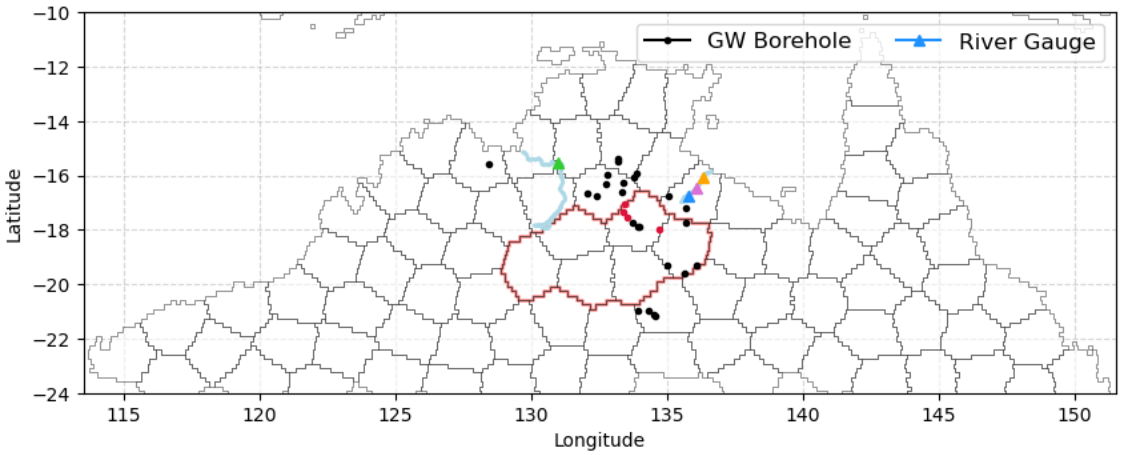


Figure 3.4: Locations of the available borehole (black dots) and river gauges (triangles) within the wet blob, overlaid on the ANU ∼200 km × 200 km mascons. The river gauges are located at Baileys Grave (blue), McArthur Mine site (pink), Borroloola Crossing (yellow) and Timber Creek (green). The red boreholes show the locations of the borehole measurements presented in Figure 3.5. The perimeter of the wet blob is shown in red.

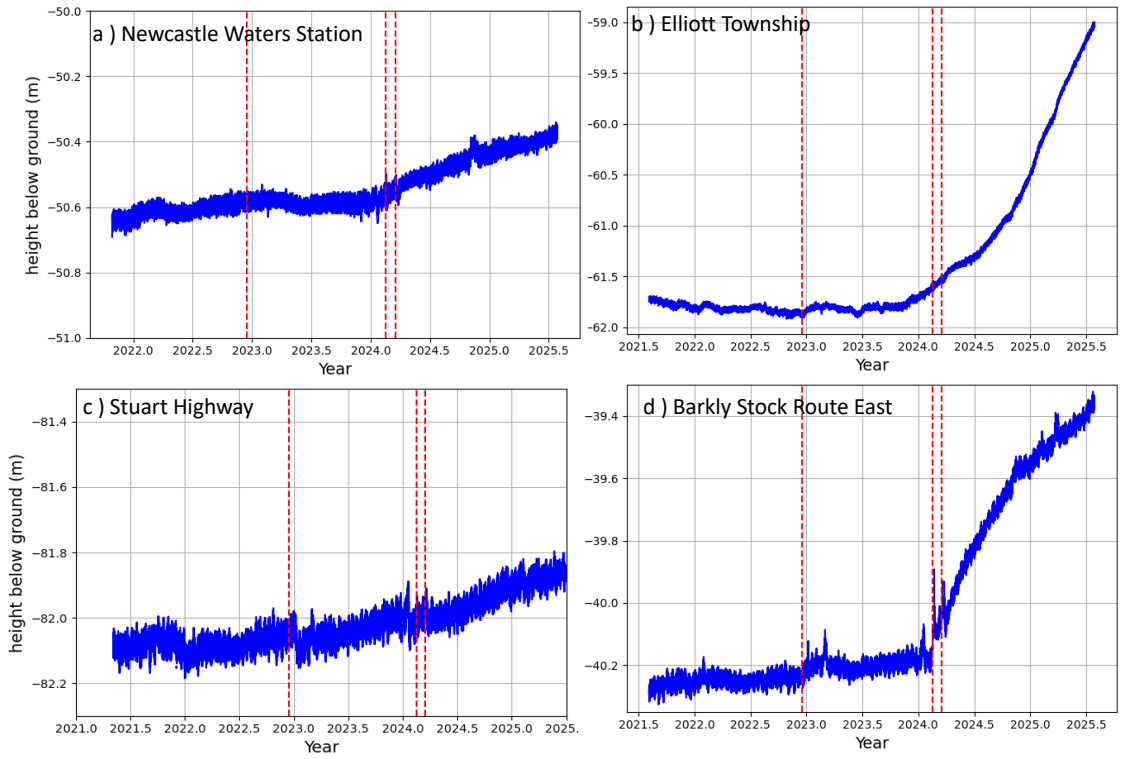


Figure 3.5: Examples of four boreholes within mascon 9228, all set to the same relative y- axis span of 1 m except for b) which spans 3 m. The red dashed lines indicate the dates of Cyclones Ellie, Lincoln and Megan. a) borehole RN040516, b) borehole RN009304, c) borehole RN038815 and d) borehole RN039070.

3.5 Results

3.5.1 Detection of Cyclone Rainfall

GRACE-FO TWS solutions are typically made available as monthly estimates; however, insights into the change in mass caused by rainfall events can be found from daily range acceleration (RA) observations. Such daily measurements from individual satellite passes have been used previously to detect floods in eastern Australia (Han et al., 2021) and the December 2004 tsunami (Ghobadi-Far et al., 2020). The inter-satellite range acceleration signals caused by mass change signals on Earth are linked through the partial derivatives relating mascon parameters to the range acceleration observations. We used the rainfall and ET data from the AWRA-L model, integrated onto the ANU mascon geometry, as a mass change signal and derived the expected RA observation as the GRACE-FO satellites flew over the cyclones:

$$RA = \begin{bmatrix} \frac{\partial RA}{\partial msc_1} \frac{\partial RA}{\partial msc_2} \cdots \frac{\partial RA}{\partial msc_n} \end{bmatrix} \begin{bmatrix} EWH_{msc_1} \\ EWH_{msc_2} \\ \vdots \\ EWH_{msc_n} \end{bmatrix} \tag{3.2}$$

where $\partial RA/\partial msc_i$ is the partial derivative relating a change in mass on mascon i to the change in range acceleration, and EWH_{msc_i} is the change in mass on mascon i. The vector of EWH values can be any quantities (e.g. total water storage change, rainfall, rainfall minus evapotranspiration) and, through Equation 3.2, the corresponding range acceleration signal can be calculated. In this case, EWH vector is the $rain - ET$ mass change. The partial derivatives, $\partial RA/\partial msc_i$ are derived when integrating the orbits of the GRACE-FO orbits and corresponding satellite position/velocity partial derivatives (Allgeyer et al., 2022).

The TWS change caused just by cyclones which occur over several days cannot be readily identified in the monthly GRACE-FO solutions. Some rainfall may be lost to evaporation prior to being detected by the GRACE-FO satellites passing over the cyclone-affected region and other rainfall may occur within the month before or after the cyclones. In order to look at the GRACE-FO data on a sub monthly scale, we compared the Line-of Sight Gravity Difference (LGD) observations (Tang et al., 2026) to the RA signal expected using Equation 3.2 and the cumulative daily *rain-ET* integrated onto the ANU mascons for Cyclone Megan in March 2024. The LGD is a newly developed GRACE/-FO data product that has been used recently to measure, for example, TWS changes caused by hurricanes in the US (Li et al., 2025). The RA is calculated using Equation 3.2 shown above where the EWH matrix is constructed with the cumulative *rain-ET* on each mascon since the start of Cyclone Megan. The GRACE-FO satellites did not always fly directly over the region where the cyclone was travelling, except for 19 and 23 March (Figure 3.6). For these days it can be seen that the computed RA signal and the observed LGD both detected a strong negative signal, which indicates an increase in the strength of the gravity signal, therefore an increase in TWS. The same can be seen for March 26th, which was after the cyclone had dissipated but most of the rain that had fallen still remained on the surface. The rainfall associated with the cyclone was expected to create a RA signal of

sufficient magnitude to be detectable in the GRACE-FO range acceleration observations and, indeed, such a signal is visible in the LGD product of (Tang et al., 2026).

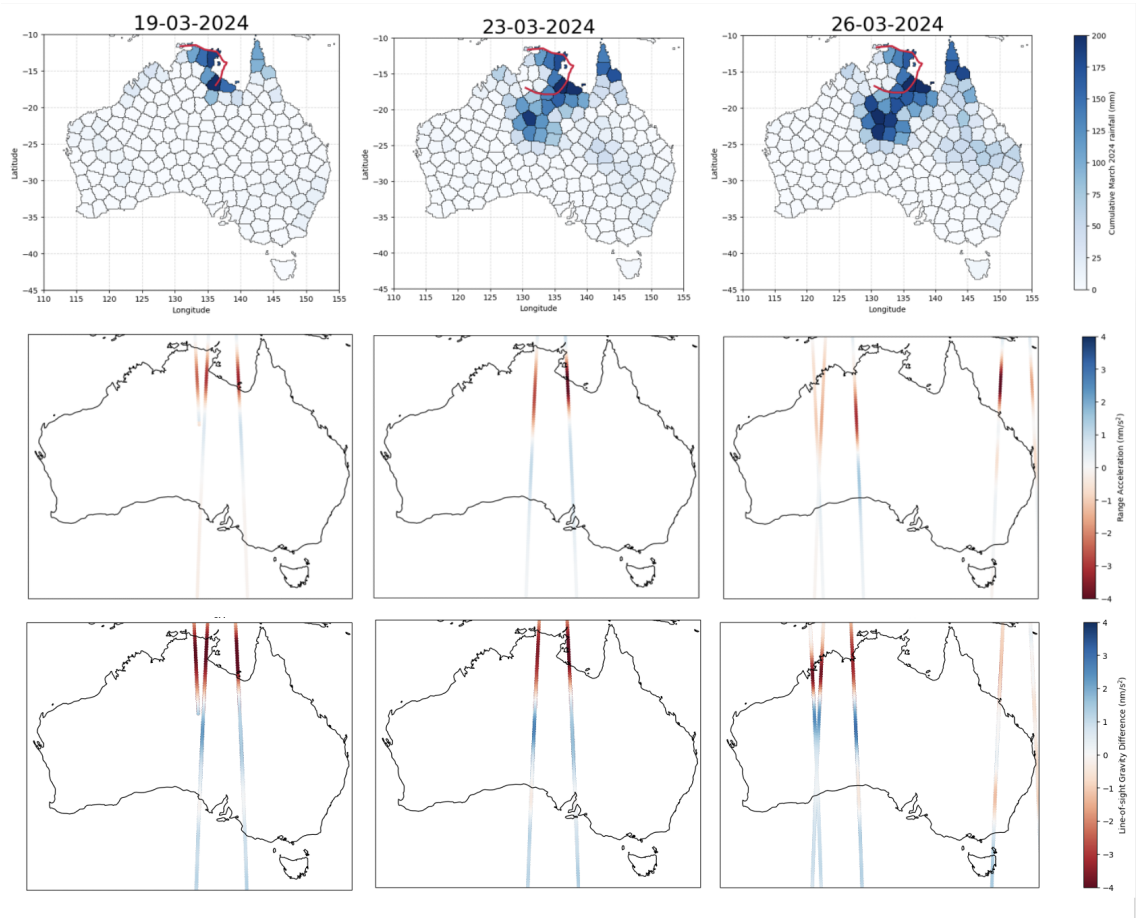


Figure 3.6: Top row: cumulative sum of rainfall minus evapotranspiration from the beginning of cyclone Megan (2024-03-14) to the end of the event, for the days where the GRACE-FO satellite flew over the wet blob region. a) 2024-03-19, b) 2024-03-23, c) 2024-03-26. The ground track of cyclone Megan is plotted in red. Middle row: range acceleration residuals computed from the mass changes of rainfall minus evapotranspiration in a-c. Bottom row: line-of-sight gravity differences for these three days using the data of Tang et al. (2026)

3.5.2 GRACE Total Water Storage Change

The region around the wet blob typically experiences strong seasonal rainfall, and cyclones during the wet season (October to March) and very little during the dry season (April to September). This seasonality can be seen in the periodic TWS changes in Figure 3.1c and Figure 3.2 prior to 2022. However, following the three cyclones in 2022 and 2024, the TWS in the wet blob region increased and has remained above pre-cyclone levels from the time of the first cyclone until the present day. The double cyclones in 2024 increased the region's TWS by approximately 600 mm at its peak in April but it then decreased over the remainder of 2024 and 2025 to approximately 150 mm. The change in TWS indicates that a significant volume of water entered the system in the region. What is curious is that this volume of water has remained in the same region for several years.

3.5.3 GRACE-FO-derived groundwater recharge

Satellite-derived changes in groundwater, GW_{GFO}, can be calculated from the GRACE-FO TWS change estimates by subtracting the *rain-ET*, changes in surface water and soil moisture from the TWS:

$$\Delta GW_{GFO} = \Delta TWS - ((\textit{rain-ET}) + \Delta Surface\ \ Water + SM_{RZ}) \tag{3.3}$$

where the surface water contribution was calculated using the river gauge stream discharge (where available), averaged over the area of a mascon and SM_{RZ} is the GLDAS root zone soil moisture layer from the surface to a depth of 100 cm.

The additional water causing the multiyear increase in TWS has either remained on the surface in lakes and soil moisture or has percolated into the groundwater. If the water has remained in the surface layers it would have likely entirely evaporated over the last two years, making GW recharge the more likely of these two possibilities. Hence, it was expected that the GRACE-FO-derived groundwater would increase across the wet blob. However, the derived GW estimates showed a consistent decrease across the study time period. This is particularly prominent in the northern mascons, where the GW appears to be decreasing by over 300 mm in some cases (Figure 3.7). The in situ GW borehole measurements show that a large decrease is not correct, hence there is a strong bias in

at least one of the datasets used to construct the GW change. The surface water, soil moisture and rain data are all based on in situ measurements, which can be externally verified and were determined not to be the likely source of the bias. Instead the bias is believed to have come from the AWRA-L ET model due to possible errors in modelling ET (Yi et al., 2024). To counteract this bias, we applied regional scaling to the ET values, based on their location's categorisation in the BOM's models. A series of scaling factors were considered for each individual mascon. The northern mascons all required an average of 120% to be applied in order to remove the bias, whereas the southern mascons only required an average scaling factor of 107%. This aligns closely with the BOM's climate zone classifications, where the northern mascons are located in the tropical savanna which recieves more rainfall on average than the southern mascons located in the warm desert zone. Hence, regional scaling was determined to be along these zones and ET values for the northern mascons were scaled by 120% and the southern ones by 107%. Applying the regional scaling, the GW measurements were recalculated (Figure 3.7) and now more closely align with the available in-situ measurements. Similar GW claculations are derived using TWS estimates from either the ANU or the COM-TG mascon solutions.

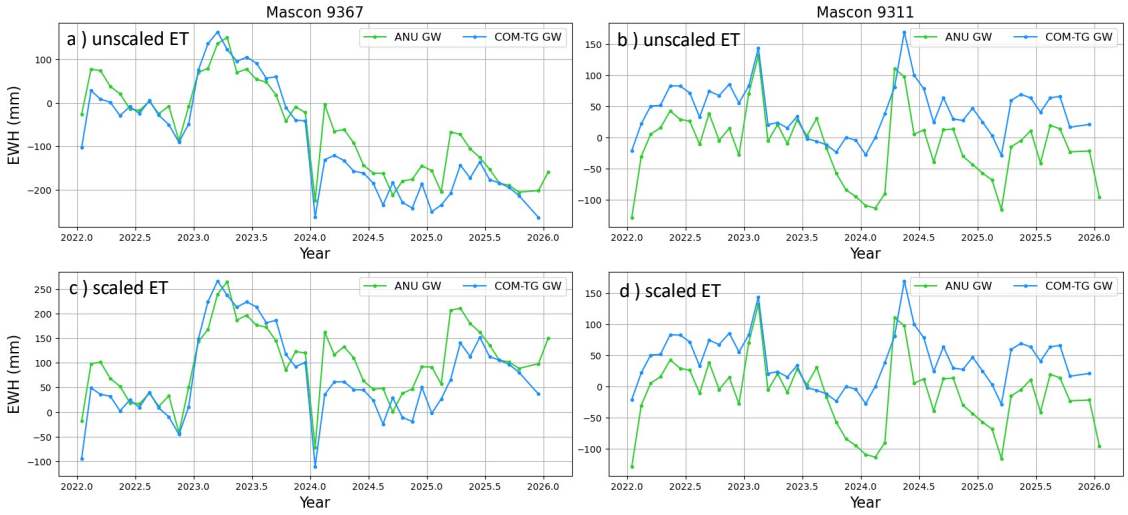


Figure 3.7: Time series showing the ANU and COM-TG solution GW_{GFO} for two mascons: 9367 which is north of the wet blob and 9311 which is south of the wet blob, where a) and b) are the the unscaled solutions and c) is the scaled solution of mascon 9367 by 120% and d) is the scaled solution of mascon 9311 by 107%.

We now compare the three different GW estimation methods used in this study, integrated over the wet blob region shown in Figure 3.1d. The first two methods uses Equation 3.2 with both an unscaled *rain-ET* and a scaling factor of 110%, being the mid point scaling factor between the two regional scales. The GLDAS model provides a third GW estimate. As can be seen in Figure 3.8, the three solutions are quite different. The unscaled *rain-ET* solution shows a decrease across the blob of approximately 380 mm from the time of the first cyclone in 2022 to the end of 2025. This decrease is not seen in any other data sets, including the GRACE-FO TWS and the in situ borehole measurements, bringing the validity of this solution into question. The second and third solutions are much more closely aligned and end at similar values in 2025.

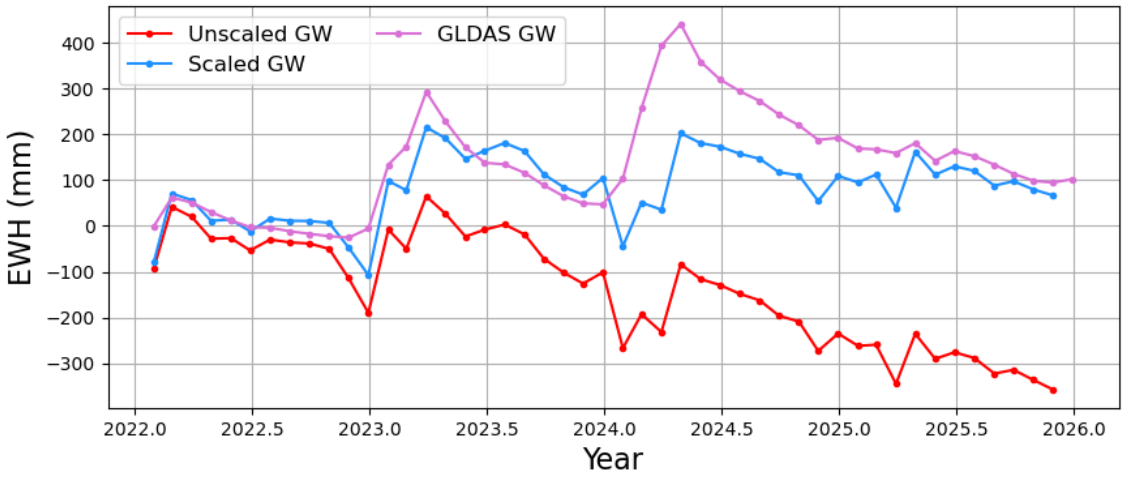


Figure 3.8: Time series of region scale groundwater change measured using the unscaled and scaled GW_{GFO} and the GW_{GLDAS} for the period 2022 - 2025

3.6 Discussion

3.6.1 Comparison between In-Situ Measurements and GRACE-FO-derived Groundwater

While the groundwater bores available in the region help to understand the groundwater storage change following the cyclones, the available bores only sample a small part of the region and are primarily located in the eastern part of the wet blob. In mascon 9228, which has the highest number of bores, the bore measurements are not even consistent with one another (Figure 3.5). Some of the boreholes show a rapid decrease in depth to groundwater (indicating GW is increasing) following the double cyclone event whereas others increase by similar amounts but at different rates. This suggests that the available boreholes, spread across different regions of the CLA, may be sampling different areas of the aquifer. As mentioned previously, the depth of the boreholes differ between bores, some sample shallow groundwater at a depth of up to 80 m while others are significantly deeper and sample to a depth of 200 m. This wide range of borehole depths may contribute to the spatial inconsistencies between borehole measurements as bores that may be very close to one another (within 1 km in some cases) can have very different depth to GW measurements. In the shallower bores the groundwater increase might occur at a earlier time than deeper bores as the water percolates at a faster rate in looser soil found near the surface.

The overall lack of borehole measurements over most of the study period and region limits their usefulness in verifying GRACE-FO-derived GW change (GW_{GFO}). Although Cyclones Lincoln and Megan were largely concentrated to the east of northern Australia, Cyclone Ellie primarily passed over the western half of the continent where there are very few bores. Cyclone Ellie passed directly over only three boreholes and there are an additional two bores that are on the periphery of the cyclone path. The three bores that do have measurements at the time of the cyclone are outside of the main wet blob mascons and show highly variable results. For one of the bores, the measured depth to water increased during Cyclone Ellie by only 200 mm whereas in a bore located 35 km away there is a measured increase of 5000 mm. Assuming a porosity of 0.3, this amounts to a difference of 1440 mm of a column of water.

Cyclones Lincoln and Megan affected a greater number of in situ borehole measurements over a wider area. These borehole measurements align much closer to the GW_{GFO} estimates. In almost all of the bores, a significant increase in groundwater was detected in the months following the double cyclones, indicating that the water that had precipitated onto the surface subsequently percolated to the depth of the upper layers of the aquifer, although this took some months to occur. After converting changes in depth to changes in TWS (using a porosity of 0.3), the bore holes show an increase in groundwater of 100 – 300 mm, consistent with the GW_{GFO} estimates in the same areas. The application of the regional scaling applied to the ET model increased the agreement between the in-situ measurements and the GRACE-FO-derived measurements.

3.6.2 Comparison between GRACE-FO-Derived Groundwater and GLDAS Groundwater

The GLDAS product we used in this study is produced by assimilating GRACE/-FO TWS measurements. Due to an absence of snow and minimal canopy interception, GW_{GLDAS} is primarily driven by TWS minus the root zone soil moisture in Northern Australia. The latter remains relatively constant (see Figure 3.3). Therefore, an almost constant value is subtracted from the TWS in order to calcualte GW_{GLDAS}, hence the values very closely follow the TWS (Figure 3.3). This is in contrast to the GW_{GFO} that was calculated by subtracting the *rain-ET* and root zone soil moisture from the GRACE-FO TWS. GLDAS provides a more simplified and global understanding of groundwater; whereas, GW_{GFO} provides a more localised understanding of northern Australia. The interpolated rain and ET model used is based on historical Australian data and direct measurements of the region, whereas GLDAS is a global land surface model that does not use extensive Australian specific data.

3.6.3 Groundwater Recharge

When viewed on a mascon scale (∼200 km × 200 km), it is clear that GW recharge is occurring in the region on a monthly timescale. The GW recharge varies spatially, in a similar manner to the regional variability of the ET measurement. To the north of the wet blob, the higher ET in the more tropical zone plays a much larger role in the

recharge process. For the majority of the northern mascons, both the rainfall and the soil moisture peak during the wet season and rapidly decrease due to the effects of ET processes. This causes seasonal peaks in the calculated groundwater changes. This pattern can be clearly seen in mascon 9298 (Figure 3.9a) where the groundwater rapidly decreases in the months following the double cyclones and then returns to a higher value during the 2025 wet season. Within the central five mascons that form the darkest section of the wet blob (highlighted in red in Figure 3.1d), the groundwater increased in 2023 following Cyclone Ellie and again in 2024 following the Cyclones Lincoln and Megan. As expected, these mascons show the highest amounts of recharge following the cyclones and continue to stay at elevated levels of groundwater throughout 2024 and 2025 (Figure 3.9). The mascons to the south of the wet blob are more variable and show a smaller increase in groundwater overall. With the exception of mascon 9214, none of the southern mascons were in the direct path of Cyclone Ellie, hence they show little recharge, consistent with having received only localised rainfall caused by the wet season. They do, however, show an increase in 2024 following the double cyclones. For the majority of these mascons, there is a spike in GW in the one to three months following the double cyclones and then a rapid decrease that aligns with the decrease in total water storage and soil moisture.

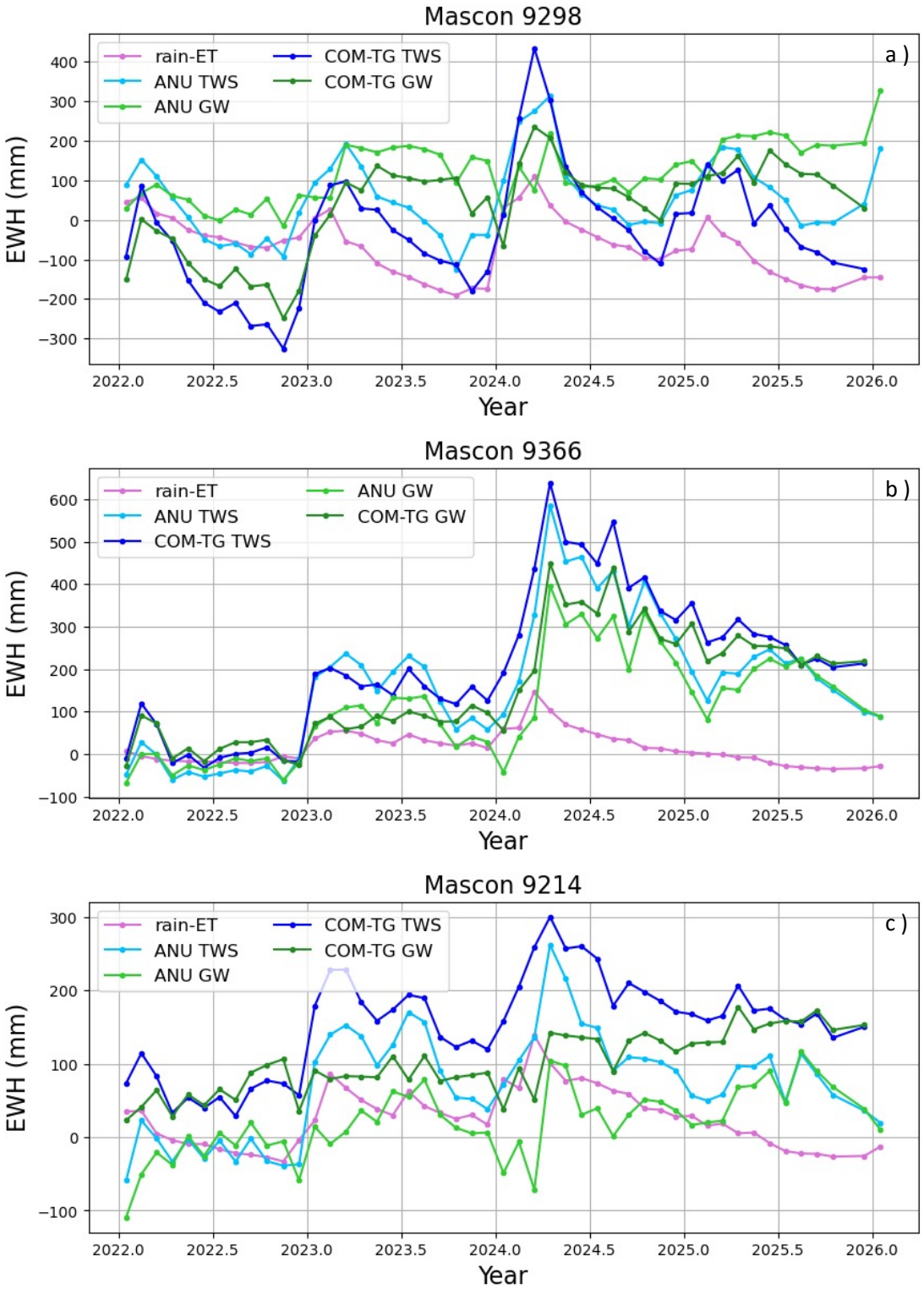


Figure 3.9: Examples of the *rain-ET*, TWS (ANU and COM-TG solutions) and corresponding GW_{GFO} estimates for three mascons within the wet blob. a) mascon 9298, in the northern tropical region of the wet blob, b) mascon 9366, in the centre of the wet blob and c) mascon 9214, in the southern arid region of the wet blob. The location of the mascons is shown in Figure 3.1d.

In general, the time it takes for water to percolate through the upper layers of the soil is debated. Baker et al. (2024) stated that recharge can happen in as little as 24 hours following a rain event, whereas Crosbie et al. (2021) claimed that it can take years for recharge to occur. As the GW_{GFO} is only available on a monthly basis, the recharge occurring from a cyclone was estimated as the change in TWS over three months after the cyclone. The integrated volume of recharge caused by Cyclone Ellie is 30.5 km^3 across the eleven affected mascons (Figure 3.10a). The volume of groundwater recharge caused by Cyclone Ellie can be identified easily as it was an isolated event. In contrast, the double cyclones happened less than a month apart; therefore, the recharge volumes of each cyclone can't be identified in the monthly GRACE-FO TWS. Instead, we calculated a four-month change in GW volume, encompassing both cyclones plus the two months following. The integrated volume of recharge from both cyclones was calculated to be 64.7 km^3 across the nine affected mascons (Figure 3.10b).

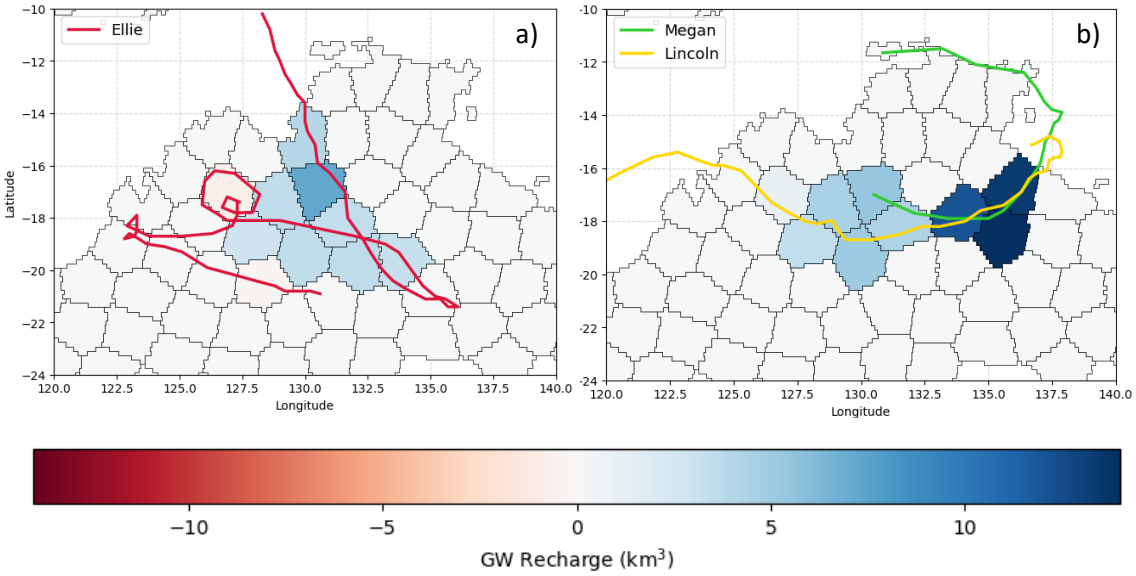


Figure 3.10: Groundwater recharge associated with the individual cyclones, calculated at the mascon scale. a) the recharge over the three months following cyclone Ellie (January, February and March 2023) and b) the recharge over the four months following cyclones Lincoln and Megan (February, March, April and May 2024)

Saleh et. al. (2025) found the volume of groundwater recharge following a single cyclone in the Arabian Peninsula to be 3.2 km^3. The cyclones that affect the Northern Territory have a much greater intensity than those in the Arabian Peninsula, hence greater rainfall. The rainfall recorded for the Oman cyclone was 617 mm, whereas the combined

rainfall for the Cyclones Lincoln and Megan was more than double at 1511 mm. Argus et. al. (2022) found the annual recharge rate of groundwater in central California to be, on average, 50 km^3. Similar to the CLA, this recharge is caused by separate precipitation events in the wetter seasons plus, unlike the CLA, the flow of snow melt through the rivers in the warmer months. Reager et al. (2026) quantified groundwater recharge in California due to snow melt at $\sim$37 km^3 during 2023, one of the wettest years on record. This recharge was caused by a TWS increase of 600 mm over the central valley in California. This is comparable to the TWS and cyclonic-driven recharge caused by Cyclones Ellie, Lincoln and Megan. These recharge rates are much larger than the typical recharge values estimated for the CLA by Crosbie and Rachakonda (2021) of only $\sim$17km^3/yr.

There is also potential that the TWS changes on each mascon were not solely driven by the *rain-ET*. Groundwater flows within the CLA in a northward direction (Taylor et al., 2024). Therefore, it is possible that some of the TWS increase is being driven by groundwater flow between the mascons. However, this flow pattern cannot be characterised simply by quantifying the groundwater difference between the mascons over time. A more complex hydrological modelling of GW flow is required to understand and quantify these processes.

The wet blob has persisted through to the present day, with moderate signs of drying in the latter half of 2025 following a wet season with no cyclones (Figure 2). However, the 2026 wet season brought high cyclonic activity in northern Australia, with a tropical low and a cyclone passing through the inland region. This has likely further contributed to the presence of the wet blob and increased the GW stores again. Given that three of the last four wet seasons have seen cyclones travel south into inland Australia, the region may be entering a new phase of regularly experiencing cyclones, with associated significant GW recharge events. This may change the long-term availability of groundwater resourses and may change the way water is managed in the region.

3.7 Conclusions

We present an assessment of cyclone-driven groundwater recharge in the Northern Territory's Barkly Region from 2022 to 2025. During that time period the region has experienced three cyclones: Ellie in December 2022 to January 2023, Lincoln in February 2024

and Megan in March 2024. These cyclones significantly increased the TWS in the region as detected by the GRACE-FO satellites and created the 'wet blob' region, a regional positive increase in TWS that persists from January 2023 through to at least September 2026. This long-term increase in TWS has been caused by a recharge of the groundwater in the aquifer. The groundwater storage increased in the CLA and surrounds by $\sim$30 km^3 following Cyclone Ellie in December 2022 with a further increase of $\sim$64 km^3 following the two back-to-back cyclones, Lincoln and Megan, in 2024. These recharge quantities are significantly higher than the normal seasonal recharge amounts for the region and indicate that cyclones can cause significant, rapid and long-lasting groundwater recharge to occur. With the intensification of cyclones due to climate change, the region could have a greater availability of GW in the future.

We show that scaling the modelled evapotranspiration is necessary to accurately calculate the groundwater change over the region from GRACE-FO estimates of TWS. When a scale factor is not applied, the GRACE-FO-derived groundwater change shows a significant loss in groundwater, which is not consistent with the increase in TWS and the larger-than-average precipitation. We found that applying scale factors of 120% and 107%, respectively, for mascons located in the northern tropical zone and arid southern zone resolved this issue.

It is important to distinguish the significant volume of recharge that was a direct result of the cyclones from the ordinary wet season recharge that occurs annually. Due to the arid nature of the region in which the wet blob formed, the recharge that occurred from the cyclones is very clear. The GRACE-FO-derived groundwater measurement in the 'neutral' year of 2022 shows little variation in all TWS components between the seasons. However, when the cyclones pass over the region the groundwater and TWS increase significantly and do not return to the previous dry season baseline. In contrast, north of the wet blob a very strong wet season signal can be seen in the subsurface components (*Rain-ET* and SM) but not in the groundwater change. Thus, the seasonal signal does not play a large part in altering the groundwater from its neutral state, making it clear that these cyclones did cause multiyear GW recharge to occur.

Chapter 4

Discussion and Conclusions

4.1 Future Water Management

Central Australia is a very dry region with little fresh water available other than from groundwater. Therefore, water allocation planning (WAP) for the Northern Territory typically aims to conserve the groundwater to sustainable limits. For the current Georgina-Wiso basin WAP, only 0.02% of the basins total storage is allocated in the plans estimated sustainable yield (ESY), which is 0.21 km^3. This very small percentage reflects the drought conditions the region was experiencing when the current WAP was drafted in 2022, however, recent events may change the conditions considered in future WAPs. Following the cyclones, the volume of groundwater was found to have increased substantially, making more available for extraction. Thus, the next water allocation plan due in 2032 may have a significantly higher ESY, which will open the region up to water intensive infrastructure.

As mentioned in Section 1.5, the Northern Territory Government is currently in the planning stages for building hyperscale AI data centres in the Barkly region, where the wet blob is located. Under the current Georgina-Wiso basin WAP, the AI data centre would consume 1.4% of the ESY set aside for economic development. Similarly, the Larrimah farms project mentioned in Section 1.5 would use an additional 5.4% of the ESY allocation. If the ESY were to increase in the next WAP, this proportion would become even smaller, potentially providing opportunity for even more water intensive projects to be developed in the region. While this is an economic benefit for the region, AI data centres and water intensive crops have a large environmental footprint. The proposed data centres will not use a closed loop water system, instead a traditional evaporative cooling system has been included in their plans (Mouat and Garnham, 2026). This design choice leads to higher water evaporation and wastage. The proposal also includes the use of natural gas as well

as solar energy to power the data centres. This gas is to be sourced from fracking in the Beetaloo Sub basin, which sits below the CLA (Mouat and Garnham, 2026). This issue has been highly contentious for many decades (GHD, 2016) and was only recently given permission to commence operations. In a region where renewable energy sources such as the SunCable solar battery project near Elliot are abundant, there are no environmental benefits in utilising natural gas. The cultivation of non-native water-intensive crops also poses a threat to the local environment. First, the expansion of agricultural practises on the previously undeveloped land is known to affect native plant diversity and richness (eg. Cavanagh et al., 2026). Second, water-intensive plants such as the proposed cotton and melons, raise the water table due to their shallow root systems and reliance on groundwater pumping (e.g Clarke et al., 2002 and Lamontagne et al., 2005). This can cause salt intrusion to the freshwater stores and subsidence of land, leading to less aquifer storage capacity (e.g. Hasan et al., 2023)

The frequency of the cyclones should also be taken into account when planning future water allocations. While the wet blob region has seemingly received a higher-than-average number of cyclones in the last 4 years compared to the previous 20 years, this may be an anomaly. Under a warming climate it is projected that cyclone intensity will increase, but their frequency will decrease (IPCC 6, 2021), hence this apparent increase in frequency of NT cyclones is unexpected. Therefore, reliance on these cyclonic events to regularly increase the GWS to the level estimated in this study should be avoided. Hence, future WAP's should continue to err on the side of caution when allocating groundwater for future projects.

4.2 Limitations of this Study

4.2.1 Data Limitations

While the results presented in this study are realistic there are limitations in the data used for analysis. The heavy reliance on modelled data that has an apparent bias in this study limits the results to a certain extent. As mentioned in Chapter 3, the ET data sourced from the AWRA-L model has a bias for the region in which the blob is located, one that caused a negative slope in the GRACE/-FO GWS. This result is unrealistic when compared to

the in-situ borehole measurements, which all showed a significant increase in GWS in the months following the cyclones. The identified bias also differed regionally, along the lines of the BOM's climate classification system. Therefore, the ET data had to be scaled to remove the bias. While the scaling chosen was based on realistic assumptions, it may not have fully resolved the error and may have re biased the data in another, unknown way. The ET analysis in the study could be improved if satellite data from CRMSET was used on its own or assimilated into the existing ET model. This was not done in this study as CRMSET is only available as monthly solutions from McVicar et al. (2022) and this study required sub-monthly solutions to better understand the cyclone events, which occur over only a matter of days.

The sole use of one soil moisture product, the GLDAS CLSM may also limit this study's results. It was noted in Crosbie et al. (2026b) that a stronger multi-model approach should be taken when deriving GWS from GRACE/-FO TWS. They presented the results from 6 different soil moisture models to show that there were stark differences between each model type. One such model they compared was the GLDAS CLSM v2.1 and v2.2 model which was used in the analysis for this study. They found that the two GLDAS CLSM models sat significantly below the other models in certain areas and above in others. While, this could highlight an error in the model, the primary reseason for this discrepancy is because the GLDAS CLSM model is assimilated with GRACE/-FO data. Thus, making the results align closer with the GRACE/-FO TWS results instead of the other soil moisture models. In addition to the assimilated GRACE/-FO data, GLDAS CLSM uses meteorological forcing data from the global ECMWF system. While this dataset has recently implemented forecasting data from the Australian ACCESS-S2 model, it is unclear whether this is back-dated from May 2025. Therefore, prior to 2025, GLDAS was potentially using meteorological data that did not contain in-situ data from Australia. Satellite measurements are available for soil moisture but were not chosen for this study as they are not available as daily measurements. The ESA CCI SM would be a better choice for the study however, available measurements end in December 2024, which is short of the study's end date of December 2025.

Finally, the monthly resolution of the TWS solutions severely limit the use of GRACE/-FO in monitoring fast-acting climate events such as cyclones. In regions such as the

Northern Territory where ET is exceptionally high, monthly measurements of TWS are unable to capture the exact dynamics of a cyclone. By the time GRACE/-FO had passed close enough to a mascon to detect changes in TWS, some of the water that was deposited by the cyclone had likely evaporated and was not sensed by the satellites. This can cause discrepancies between the TWS data and the rain-ET, which are both used to calculate GWS. Attempts have been made to estimate TWS on a sub-monthly scale; however, the accuracy of these methods is uncertain and may impact the results more so than the missing observations (e.g Rateb et al., 2024). GRACE/-FO TWS also senses all layers in the water column, many of which can be removed by modelling. However, it was noted in Castelazzi et al. (2024) that if GWS is being calculated for a specific aquifer layer it can be overestimated by the presence of unaccounted for shallower aquifers that cannot be easily removed with models or in situ measurements.

4.2.2 Methods Limitations

Other limitations with this study lie in the assumptions made in the quantifying of surface processes and surface water. First, a direct measure of surface runoff was not included in the calculation of the GRACE/-FO derived GWS. This assumption was made due to the lack of suitable runoff models and lack of rivers and streams in the wet blob. There is a surface runoff component of the AWRA-L model; however, open water storage such as lakes are not included in the model (Frost et al., 2021). As the majority of surface water is stored in ephemeral lakes in the wet blob region, it is important that a chosen model reflects this. The region also only contains two major runoff discharge points: the Victoria and the McArthur Rivers which flow out to the ocean. Hence, little runoff other than flood water would be able to leave the region, and most of this flood water would be eventually percolate into the soil moisture or evaporate. The aforementioned rivers also both contain river gauges that were included in the study; however, the Victoria River only has one river gauge active near the wet blob and there are other tributaries that flow into the river from the wet blob further downstream and are therefore not accounted for in the measurements of this gauge.

Surface water is another component of the GRACE/-FO derived GWS where assumptions were made. As mentioned, the surface components, including surface water of the

GWS were accounted for by river gauges located on the fringe of the wet blob (Figure 3.4). However, as also mentioned in Section 1.4, the wet blob region contains a system of large ephemeral lakes that can store water for up to 12 months following significant rainfall. These lakes have no in situ gauges and can only be observed using remote sensing. This includes the Surface Water and Ocean Topography (SWOT) mission which measures water height as well as extent. However, the readily available Prior Lakes Database (PLD) which has predefined water extent for significant lakes globally is not very accurate for Australia (Maubant et al., 2025). Although the wet blob has five lakes, only the smaller Eva Downs Swamp is defined in the PLD, with the others missing or only partially defined. This can be seen in Figure 4.1 which shows the PLD extent for August 2026 compared to the Normalised Water Difference Index (NDWI) which is used to detect regions of water, shown over the same period. This clear difference severely limits SWOT's usefulness in this study, especially as the lakes are ephemeral water bodies, which are known to lose their water to groundwater over time. The pixel cloud data could also have been used to measure the height of the lakes, but this is beyond the scope of the study.

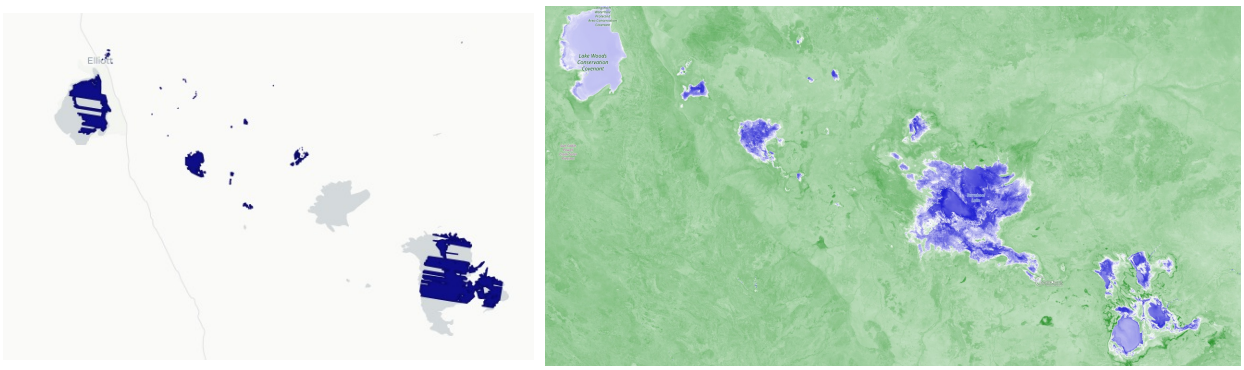


Figure 4.1: SWOT PLD definitions for the Barkly Region's lakes in August 2026 (left) compared to the NDWI classifications from Sentinel-2 for the same region in August 2026 (right).

4.3 Future Directions

4.3.1 Improvements

The work developed through this study could be taken further in a number of ways, primarily to better understand groundwater behaviour not just in the Northern Territory but in semi-arid basins around the world. A process that was looked at but eventually

deemed outside of the scope of this study was to use the GRACE/-FO derived GWS to measure groundwater flow in the CLA. At first, it was assumed that the flow pattern could be estimated on a month-to-month basis by tracking the movement of the TWS signal. It is well documented that groundwater in the CLA flows to the northwest/northeast depending on the basin in which it originates (e.g. Taylor et al., 2024), hence this flow should be easy to observe. However, this simplistic view did not capture the complex hydrological processes occurring. Therefore, groundwater flow was not measured as part of this study. Future work could be done to develop a more complex groundwater flow model suitable for the CLA, using the GRACE/-FO derived GWS. If the GRACE/-FO derived GWS were to be calculated for other semi-arid basins outside of Australia, similar groundwater flow models could be developed as well.

The analysis conducted on this study could be further improved by assimilating the soil moisture, ET and rainfall data into a land surface model that is specific to northern Australia. In doing so, many of the data limitations mentioned in section 4.2.1 would no longer affect the results. For example, data assimilation would remove the suspected AWRA-L model errors from the ET measurements used, hence there would be no need to scale the results in order to match the in-situ measurements. It would also improve the generalisations made by using GLDAS, which applies a blanket porosity of 0.3 to the region. This porosity differs from the variable porosity noted in Taylor et al. (2024), who investigated groundwater in the same region as the wet blob. Inclusion of SWOT mission data in the study would also improve the results. As mentioned previously, the regions lakes are missing or partially defined in the SWOT PLD, but there are other datasets that do not rely on these definitions. These alternative SWOT products include the PIXC data which is a pixel cloud of geolocated water height data. This process was not essential for the specific region investigated in this study but could be important for basins with significantly more surface water storage that may not be ephemeral.

4.3.2 Recent Cyclones

The 2025/2026 Australian cyclone season began in mid-November 2025 and increased rapidly with 6 cyclones of category 1 or above recorded by the end of the year. In total there were 16 cyclones across Australia, two of which passed close to directly over the

wet blob region. The first was a minor tropical low from December 14th, 2025 – January 2nd, 2026, that caused 150 – 250 mm of rainfall across the region. The second was Severe Tropical Cyclone Mitchell which passed over the northern section of the wet blob, near the town of Larrimah. The weekly rainfall totals exceeded 200 mm across the northern wet blob, with the area around Bradshaw receiving over 150 mm of rain in the span of 24 hours. Cyclone Mitchell caused flooding in the Daly River to the north of the wet blob and more flooding in the Pilbara region of Western Australia.

These two events have further increased the GRACE/-FO TWS in the wet blob to levels that are greater than the TWS change caused by the double cyclones in 2024 (Figure 3.2). Given their similarity, it is highly likely that the two most recent events have recharged the GWS at the same or even higher volumes as the 2024 double cyclones assessed in this study. As 2026 specific data becomes available a new estimate for GWS could be calculated for the region. However, some of the borehole measurements used to observe GWS are no longer active in the region. A majority of bores surrounding Lakes Tarrabool and Sylvester have been non-operational since September 2025, leading to even less in situ data being available.

In addition to quantifying the GWS, work could be done to understand the observed trend in cyclone activity over the last four years. As stated previously, under a warming climate cyclone activity is expected to decrease but intensity increase (IPCC 6, 2023). However, it appears from this very small subset of data that cyclonic activity in the Northern Territory is increasing. It is vital for future water allocation planning to understand if the current frequency of these events define a new normal or whether this is an anomaly.

4.4 Conclusions

This study has shown that cyclonic activity in the Northern Territory between 2022 and 2025 has recharged the underlying groundwater aquifers. Through combining GRACE/-FO TWS measurements and modelled data, the recharge volume over three months following Cyclone Ellie in December 2022 was found to be 30.5 km^3 and the recharge volume in the four months following Cyclones Lincoln and Megan was found to be 64.7 km^3. These recharge volumes led to a significantly higher recharge rate than the assumed recharge rate used to calculate the ESY for the Georgina-Wiso water allocation plan. This may

alter the types of projects approved for water licences, especially with the precedent set by the proposed AI data centre development and water intensive farming. However, the environmental impacts of these projects should still be carefully considered even if there is enough available water for them to operate.

This study relied very heavily on modelled results, which may have biased the results and is limited by the monthly resolution of the GRACE/-FO results. In future the accuracy of the models that are relied upon could be improved by assimilating other data sources, such as remote sensing data. Better understanding of the climate drivers behind the apparent increase in cyclonic activity would also improve the results of this study. This would allow for future water allocation planning to be better managed and make these large groundwater recharge events more predictable. As groundwater recharge patterns change under a warming climate, it is becoming vital that semi-arid basins like the CLA are better understood and can be sustainably maintained for generations to come.

Chapter 5

Reflection

5.1 What you have learned by doing research

Since commencing my Masters in Earth Sciences, I have greatly improved my understanding of the process of conducting research. While my undergraduate degree in Physics and Maths did have a research component and I did undertake some research in the geomorphology of sand dunes on the Young Husband Peninsula, I was not able to dedicate the same amount of time that I have been given for this project and as such did not fully develop my research skills before starting my Masters. By focusing on research methods in the first year of my Masters, with courses and my Special Topics project on *Investigating Antarctic Bottom Water Through the Orkney passage* I was able to broaden my skills, particularly in coding and began developing my understanding of the research methodologies that I would need to apply to my masters thesis project.

Prior to beginning this Masters, I did not have the opportunity to develop an understanding of coding languages and specifically I had no understanding of Python, nor did I have any experience in applying coding to research. The ability to code and its application to my data in my research has been critical to the completion of my analysis of both GRACE/-FO satellite data and modelled data. The entirety of the analysis of my Masters Thesis project and my Special Topics project have been conducted with Python. In addition to my research providing a solid understanding of Python, I have also had the opportunity to adapt models and therefore am now able to analyse and apply modelled data when appropriate to my research. My Masters Thesis project has also, obviously, given me a much greater understanding of the current state of research in my field as I have needed to review the literature last year for my thesis proposal and again this year for completion of this Thesis.

While in my undergraduate degree, I was required to regularly write scientific reports, this Master's is my first opportunity to write so extensively on a single piece of research. It has also provided me with the opportunity to complete my first paper for publication. Having guidance from my supervisor and his being my co-author on the paper has helped strengthen my tone and my professionalism in my scientific communication.

5.2 New ideas and perspectives formed during the research

During the writing of my research proposal last year, I thought I would be using more remote sensing techniques to measure the layers of the water column. However, once I began my Thesis project this year I rapidly concluded that none of these measurements would be suitable for the data I had in hand. I instead I pursued a model centric approach to achieve my research aims. I also had the intention of observing ground water flow with my data and spent a considerable amount of time following this approach. Ultimately, I had to conclude that it was not possible without developing a much more complex hydrological flow model which could not be achieved in the time I had to complete this piece of research. It is something that I would like to consider should I have the opportunity to pursue further research. From the beginning of this project I believed that I would be able to use bore data to substantiate and verify data from GRACE/-FO. While I was able to use some bore data in my analysis, unfortunately there are even less bores and therefore bore data available that I initially realised, which inhibited my ability to analyse one of the cyclone events.

5.3 Conclusion

I have enjoyed the challenge that this thesis and publishing a paper has posed. Whilst at times I would have liked the process to have been a bit smoother and more straightforward, I find this topic fascinating and believe my research makes a vital contribution to our understanding of groundwater in this extremely remote region and how remote sensing can improve estimated volumes of groundwater.

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