Monitoring groundwater storage in the Great Artesian Basin through remote sensing: the Surat Basin

A report completed for Geoscience Australia

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Executive Summary

Remote sensing satellite data offers the possibility of quantifying changes in groundwater storage at the broad continental and/or basin scale and, possibly, at the sub-catchment scale. Through quantification of changes in total water storage, using data from space gravity missions and of non-groundwater hydrology signals with modelled values from land surface and hydrology models, it is possible to estimate changes in groundwater. Essentially, groundwater is what is left when all the non-groundwater hydrology signals are subtracted from the changes in total water storage.

In this report, we have compared total water storage (TWS) estimates derived using two mass concentration (mascon) regions configured to match geometries of: 1) surface drainage basins and 2) aquifers across Australia. We found that the differences in these estimates of TWS change across Australia are typically less than 10 mm of equivalent water height before 2010 but can reach as much as 15 cm between 2010 and 2016. Therefore, the geometry used to construct the mascon pattern can affect the groundwater storage (GWS) change estimates.

To isolate the groundwater changes it is necessary to remove the other water components such as soil moisture, surface water, canopy water and snow. To quantify these non-groundwater components, we used three different hydrology/land surface models: Global Land Data Assimilation System (GLDAS)-"Noah"; GLDAS-Catchment land surface model (CLSM); and the Bureau of Meteorology (BoM) Australian Water Resources Assessment (AWRA) soil moisture values. These models were found to be in agreement, in a broad sense, but unfortunately differ significantly at times when large changes occur in the magnitude of any of the water components. In particular, during the very wet period in Australia of 2010-2013, the modelled values differ between models by as much as 200%.

The three modelled estimates of changes in groundwater, integrated over the Surat Basin, show multi-year variations with a consistent significant increase of estimated groundwater across the three models in 2010-2013. These years correspond to a period where Australia received increased rainfall after the breaking of the Millenial drought. The linear rate of change of groundwater over 2003-2016 is 8±1.5 mm/yr.

We computed the overall uncertainty of the GWS change estimate as the in-quadrature summation of the uncertainty of the TWS estimate and the root-mean-square of the three hydrology model values, at each epoch. The root-mean-square of the three hydrology model values dominates the error budget, with uncertainties reaching as much as 10 cm during the wet period in 2010-2013.

The geodesy group of the Research School of Earth Science (RSES) of the Australian National University (ANU) has developed approaches to estimate changes in groundwater storage (GWS) over the Australian continent using remote sensing data.

The following report explains the data sets and models that we have used, along with the mathematical concepts and interpretations. We outline the limitations of the study and suggest future work.

Introduction

The most important source of water to billions of people in terms of agriculture, industrial, and domestic activities is groundwater (Siebert et al., 2010). This important water component has been affected by climate changes both directly (effects on reservoirs and fluxes) and indirectly (human activity, groundwater use) (Green et al., 2011; Döll, 2009). Therefore, a long-term reliable evaluation of this component is necessary for water managers to make more sustainable decisions.

Monthly gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) space gravity mission (Tapley et al., 2004) provide a quantitative time-variable estimation of total integrated water mass change. Therefore, long-term total water storage (TWS) is available from observations of monthly gravity changes and, combined with a hydrology/land surface model, is an alternate means to estimate and monitor groundwater storage (GWS).

Changes in groundwater cannot necessarily be derived directly from GRACE data because the total water storage estimates are the integrated sum of changes in groundwater, deep and shallow soil moisture, surface water and any other processes that may have caused a change in mass in a location (e.g. glacial isostatic adjustment, tectonic uplift/subsidence, significant erosion events etc). Across Australia, the water-related signals dominate known sources of the mass change signals detected and any other effects can be ignored.

Monthly total water storage estimates covering Australia were provided to Geoscience Australia from the ANU GRACE team as part of the Northern Australia project. These estimates were calculated on a spatial pattern of mass concentration (mascon) regions which were configured to match the drainage basins of Australia, and are used in this study. Changes in groundwater from 2003 to mid-2016 are derived by removing other water components (soil moisture, canopy and snow water) from the GRACE-derived TWS. The uncertainties of the estimates, therefore, include both GRACE TWS uncertainties and hydrology model uncertainties; however, the GWS uncertainties are dominated by the components from the hydrology models.

In this report we provide monthly GWS changes on mascons across Australia, using a mascon geometry which follows the pattern of surface drainage basins and sub-catchments. We also provide an alternate set of estimates where we have configured the mascons to follow the aquifer geometry instead. We describe the characteristics of the three hydrology models that we have used to quantify the changes in soil moisture, canopy and snow water. We look in detail at changes in the Surat Basin and focus on assessing the uncertainties of the GWS estimates and how differences in the hydrology model values are most significant during the times of large total water storage changes. We discuss how alternative approaches to deriving GWS from TWS may lead to more reliable quantification of the GWS changes.

Funding for this project was provided by Geoscience Australia as a component of the Great Artesian Basin Groundwater Project funded through the Australian Government by the National Water Infrastructure Development Fund. The outputs of this project are publicly available through an ANU-hosted website.

Hydrology Models

NASA GLDAS models

In 2004, NASA introduced Global Land Data Assimilation System (GLDAS) products with the purpose of generating land surface states and fluxes by integrating satellite observation and ground-based data sets through land surface models and data assimilation (Rodell et al., 2004). These products contain land surface models (Noah, Catchment (CLSM), the Variable Infiltration Capacity (VIC), and the Community Land Model (CLM)), land surface states (soil moisture, snow, and temperature), and fluxes (evaporation and sensible heat flux). There are currently two different versions of GLDAS (GLDAS-1 and GLDAS-2). The main differences between the two models are different forcing models, upgraded Land Information System (LIS) software, and longer time series of the results for the GLDAS-2 models. Each version of GLDAS-1 and GLDAS-2 has its own components with different characteristics. Since we only used GLDAS-2.1 (Noah land surface model) (Beaudoing, 2020) and GLDAS-2.2 (Catchment land surface model (CLSM)) (Li et al., 2019) in this study, we discuss only the details related to these two models.

The simulation for GLDAS-2.1 started at 1/1/2000 using the initial conditions of the GLDAS-2.0 simulation. This simulation was forced by Atmospheric Administration (NOAA)/Global Data Assimilation System (GDAS) atmospheric analysis fields (Derber et al., 1991), the disaggregated Global Precipitation Climatology Project (GPCP) V1.3 Daily Analysis precipitation fields (Adler et al., 2003; Huffman et al., 2001), and the Air Force Weather Agency's AGRicultural METeorological modelling system (AGRMET) radiation fields.

The GLDAS-2.2 simulation started at 1/2/2003 using the starting values of the GLDAS-2.0 simulation. This simulation was forced by the meteorological analysis fields from the operational European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System.

BOM AWRA

In addition to the two global GLDAS models, outputs from a national hydrology model provided by the Bureau of Meteorology (BoM) have been used to quantify soil moisture changes.

The Bureau of Meteorology uses the Australian Water Resources Assessment Landscape (AWRA-L V6) hydrology model which produces daily (or monthly) products describing a distributed water balance. The product is the result of the simulation of water flow on the landscape from rainfall, entering grid cells through the vegetation and soil moisture stores and exiting the grid cell through evapotranspiration, runoff or deep drainage to groundwater systems (Frost et al., 2018).

This national-scale model, henceforth called AWRA, provides two types of products as actual and relative data. In this study, we used actual data sets which are the actual percentage of the available water content instead of actual total soil water volume or depth.

The basic characteristics of these different hydrology/land surface models are given in Table 1.

***Table 1**. Characteristic of the hydrology models.*

Content	GLDAS/NOAH	GLDAS/CLSM	AWRA
Format	NetCDF	NetCDF	NetCDF
Latitude Extent	-60° to 90°	-60° to 90°	-44° to -10°
Longitude Extent	-180° to 180°	-180° to 180°	112° to 154°
Spatial Resolution	0.25°	0.25°	0.05°
Temporal Resolution	monthly	daily	Monthly
Temporal Coverage	1/1/2000 – 1/1/2020	1/2/2003 – 1/1/2020	1/1/2000 – 1/1/2020
Spatial Coverage	Global	Global	National

Since the two GLDAS models have spatial resolutions of 0.25°, we have downscaled AWRA to the same resolution to make the hydrology models consistent. Also, GLDAS/CLSM products provide daily data from which we generated monthly-averaged values to ensure temporal consistency among the data sets.

ANU GRACE solution

We used the ANU GRACE software to process the Level-1B data of the GRACE mission to make daily estimates of the changes in the Earth's gravity field. Because of the altitude of the satellites, there is insufficient ground track coverage in a single 24-hour period to permit an accurate estimate of the entire global temporal gravity field. Therefore, we combine daily estimates over a calendar month to produce monthly estimates. This process has been described in an earlier report (Tregoning et al., 2020).

We estimate changes in mass on the surface of the Earth, representing the change as an equivalent water height over specific mass concentration (mascon) regions. The height of water estimated times the area of the mascon then yields the change in volume of water for that mascon region.

Geometry of ANU GRACE mascon solutions

The geometry of the mascons is arbitrary and we have used two different, independent mascon geometries. First, we configure the mascons so that their shapes follow the boundaries of surface drainage basins over Australia. For the other mascon geometry, the mascons are configured to follow the shape of aquifers across Australia. We then segment each of these broad-scale "regions" (either surface drainage basins or aquifers) into individual mascons of a particular area, roughly ~300 x 300 km. We then estimate changes in equivalent water height on each mascon required to make the orbit modelling of the GRACE satellites match the mission observations.

The impact on the estimates of total water storage changes, and hence groundwater storage changes, is described later in this report.

Integration of the water components on the ANU GRACE primary mascons

Since the TWS has been derived from ANU GRACE gravity solutions, we need the water components of the hydrology models integrated over the spatial extent of the mascons to ensure a consistent estimation in terms of spatial resolution. Therefore, every hydrology component (layers of soil moisture, canopy surface water and snow water) has been calculated on the coordinates of the ternary mascons within each primary mascon. By adding them together we derive the value for each primary mascon. That is, each water component of a primary mascon has been calculated as:

$$P_w = \sum_{i=1}^{n} W_t(i) \times area_t(i) / area_P \quad \#(1)$$

where W_t is the value of the water component on a ternary mascon, $area_t$ is the area of the ternary mascon and $area_P$ is area of the primary mascon. n denotes the number of ternary mascons within each primary mascon. We can then express the amount of each water component in terms of an equivalent water height across each primary mascon.

Estimating GWS

According to the water balance equation, which is based on the principle that the flow into and out of a system must be equal under equilibrium conditions (Rodell et al., 2007), TWS flow into and out of the landscape must be the same. The TWS includes the contribution from soil moisture, surface water, canopy water storage, snow water equivalent, and the groundwater storage. Therefore, the components of the water balance equation can be expressed as:

$$TWS = SM + SW + CW + SWE + GWS \quad \#(2)$$

Rearranging Equation 2, we can find the groundwater storage change:

$$GWS = TWS - SM + SW + CW + SWE \quad \#(3)$$

Water Components

Soil moisture is the largest component used in the water balance equation, in comparison to canopy and snow equivalent water height. This component has been observed and calculated differently in our three hydrology models, as can be seen in Table 2.

While the Noah model separates the soil moisture into four vertical levels (up to 2 m depth), the CLSM model only provides surface, root zone and profile soil moisture. Root zone soil moisture has a uniform depth of 1 m in CLSM, however in Noah, this variable depends on the vegetation type: for grass it is the sum of the first three layers and for forested areas it is the sum of all four layers.

AWRA provides three different soil moisture layers up to 6m depth, but this model does not provide snow and canopy equivalent water height. We supplement these components in the AWRA model calculations by using the values from the Noah model.

Table 2. *Water Component provided by GLDAS/Noah, GLDAS/CLSM and BOM.*

Model	GLDAS/CLSM	GLDAS/Noah	BOM
Soil Moisture Layers	Surface soil moisture (0 - 2cm) Root zone soil moisture (0 - 1m) Profile soil moisture (varies grid by grid)	Soil moisture – Layer 1 (0 - 10cm) Soil moisture – Layer 2 (10cm - 40cm) Soil moisture – Layer 3 (40cm - 1m) Soil moisture – Layer 4 (1m - 2m) Root zone soil moisture (varies based on vegetation)	Upper layer soil moisture (0 - 0.1m) Lower layer soil moisture (0.1 - 1m) Root zone soil moisture (upper layer + lower layer) Deep layer soil moisture (1 - 6m)
Canopy surface water	✓	✓	✗
Snow water equivalent	✓	✓	✗

Case Study: The Surat Basin

One of the sub-basins of Great Artesian basin (GAB), the Surat Basin is located on the south-central Queensland and north-central New South Wales. There are three main primary mascons of the ANU mascon solutions located spatially in this basin, as shown in Figure 1. The left panel of Figure 1 shows the primary and ternary mascons when the geometry of the gravity solution has been constrained by the surface catchment boundaries. A mismatch occurs in regards to the actual boundary of the Surat basin because of the use of surface basin geometry rather than aquifer geometry. This mismatch can be rectified using the second ANU GRACE solution which has been configured using aquifers over Australia. Note, however, that in either case the estimates of change in mass of the mascons is a sum of both surface and groundwater mass changes. Simply changing the geometry of the mascons to match the aquifer geometry does not mean that the surface hydrology signals have been eliminated.

The yellow, purple, and green stars on Figure 1 show the locations of the ternary mascons comprising each primary mascon. Table 3 gives the coordinates of the Surat basin’s primary mascons in both of the ANU GRACE gravity solutions.

***Table 3**. Coordinates of the primary mascons in the Surat Basin used in the two ANU GRACE gravity solutions. Colours are consistent with Figure 1.*

Solution	Yellow	Purple	Green
Constrained surface catchment geometry	$-27.88^{\circ}, 148.53^{\circ}$	$-28.60^{\circ}, 150.85^{\circ}$	$-31.10^{\circ}, 149.05^{\circ}$
Constrained aquifer geometry	$-26.56^{\circ}, 148.51^{\circ}$	$-30.44^{\circ}, 148.50^{\circ}$	$-27.78^{\circ}, 150.45^{\circ}$

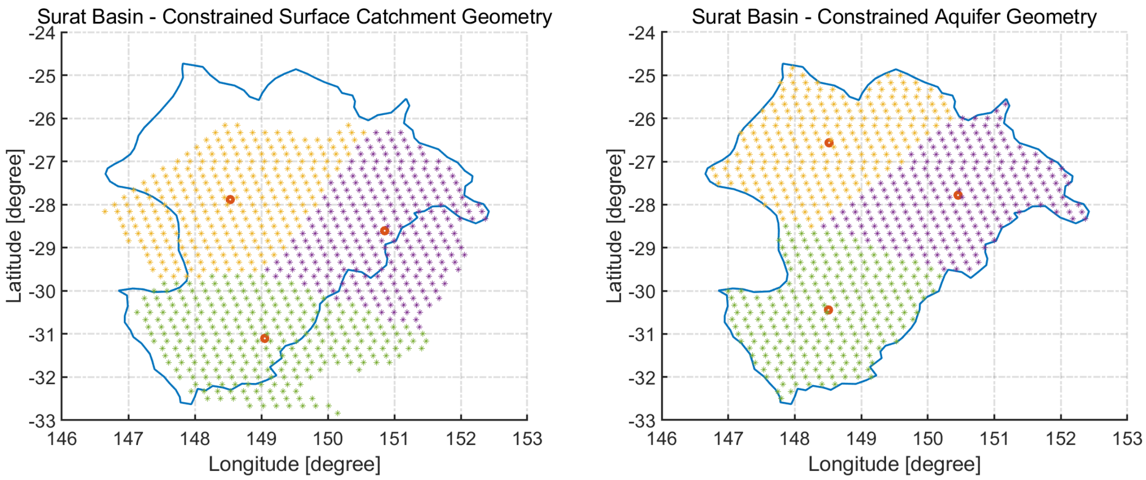

***Figure 1**. The Surat Basin; located in south-central Queensland and north-central New South Wales. The mascon geometry is based on constrained surface catchment geometry (left) and constrained aquifer geometry (right). Red circles are the locations of the centres of mass of primary mascons and yellow, purple and green stars show the corresponding ternary mascons for each primary mascon.*

We generated time series of total GWS estimates from 2003 to mid-2016 over the Surat Basin (Figures 2 and 3). Water components have been calculated using Equation 1 for each primary mascon for each of the two GRACE solutions, and GWS has been estimated using Equation 3 over the area of each primary mascon. Figure 2 shows the GWS when the TWS has been derived from a constrained surface catchment geometry solution and Figure 3 shows the result with the constrained aquifer geometry. Although a clear mismatch between the basin's boundary and the mascons can be seen in Figure 1, there is no significant change in the GWS derived from using mascons from a constrained surface catchment geometry solution (Figure 2) and the results using the constrained aquifer geometry (Figure 3).

We calculated the uncertainty of the estimated GWS changes as:

$$\sigma_{GWS} = \sqrt{(\sigma_{TWS})^2 + (\sigma_{SM})^2} \#(4)$$

where the σ_{TWS} has been provided for each primary mascon along with the corresponding EWH value for each epoch, and σ_{SM} has been determined by computing the root-mean-square

(RMS) of the three hydrology model values at each epoch. GWS changes – or anomalies – are calculated by removing a mean value over the period 2003 to 2016 from each data set (GRACE mascons and hydrology models). According to Figures 2 and 3, GWS changes over the Surat Basin show a slightly increasing trend of about $8 \pm 1.5\ mm/yr$. The trend is statistically significantly different from zero.

The uncertainty of the estimated GWS varies from about $1 - 10\ cm$ (Figures 1, 2). The GRACE TWS uncertainties are only about *7 mm*, hence contribute little to the total GWS uncertainty. The majority of the uncertainty comes from σ_{SM} (Equation 4) because of the differences between values from the hydrology models. This can be seen most clearly from 2010 to 2013 when the uncertainty of the estimated GWS reaches $\sim 10\ cm$ while the TWS uncertainty remains at only about $7\ mm$.

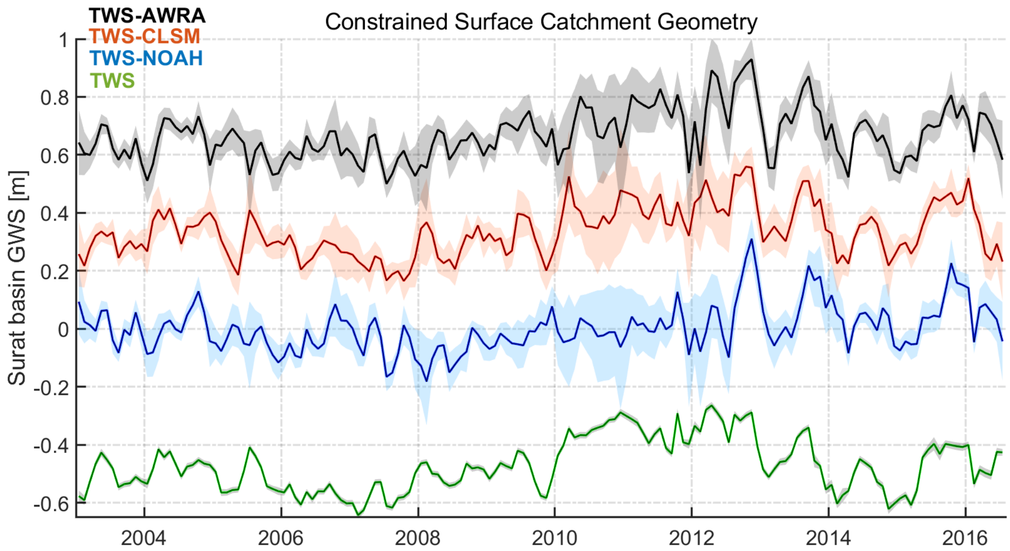

***Figure 2**. GWS estimates for the Surat Basin using the mascon geometry constrained to surface catchment boundaries and the three different hydrology model estimates used to remove non-groundwater signals from the GRACE-derived total water storage values. Time series have been plotted with artificial offsets to permit better comparison; TWS-Noah (blue), TWS- CLSM+0.3 m (red), TWS-AWRA+0.65 m (black). The GRACE-derived TWS (with -0.5 m offset) is shown (green). An average over the period 2003 to 2016 has been subtracted from each data set.The uncertainty envelope around each line denotes the uncertainties of the GWS estimates.*

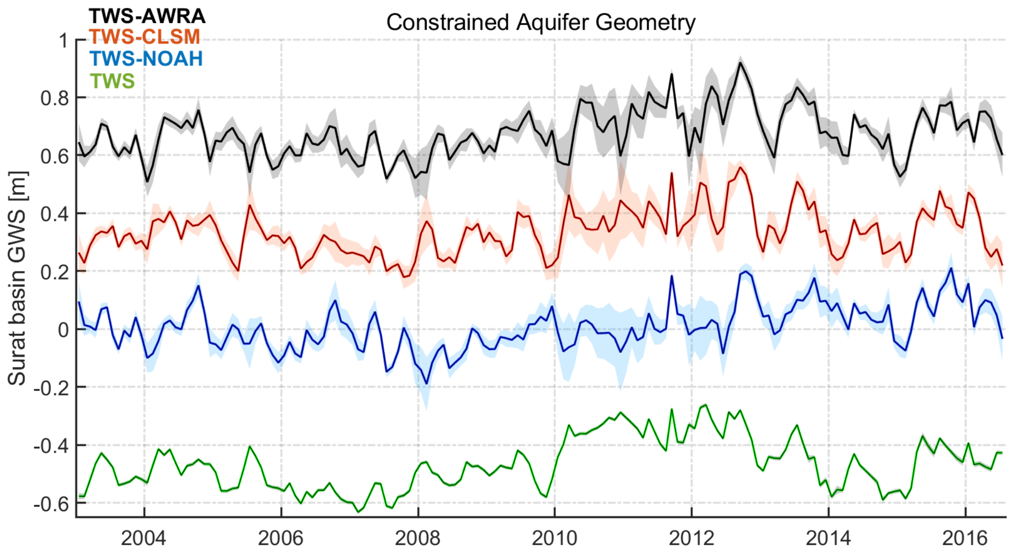

***Figure 3**. As for Figure 2 but using the mascon geometry constrained to aquifer boundaries.*

The three modelled values of non-groundwater changes in water storage from the three hydrology models are shown in Figure 4. The broad-scale pattern of peaks and troughs is represented, at least to some extent, in each of the hydrology model outputs and, for much of the time series, the RMS of the difference between the three modelled values at each epoch is < 5 cm. We use this RMS value as a measure of the uncertainty at each epoch of any of the three modelled hydrology values.

During periods of significantly low modelled water levels (e.g. 2006-2008) or high modelled water levels (e.g. 2010-2012), the differences between the modelled values are greater, at times causing the RMS at each epoch to increase to over 10 cm. These differences in modelled values cause the respective estimates of groundwater change to vary considerably, and the corresponding uncertainties of the groundwater change estimates (calculated using Equation 4) to increase accordingly.

Although this impacts upon the ability to interpret the groundwater changes derived using this approach, it is not related to any inherent weakness or issue in the estimates of TWS from the GRACE data itself. Independent assessment of the three hydrology model outputs – perhaps against in situ observations – is required to discern which, if any, of the modelled values are more accurate in the Australian region. This is beyond the scope of this study.

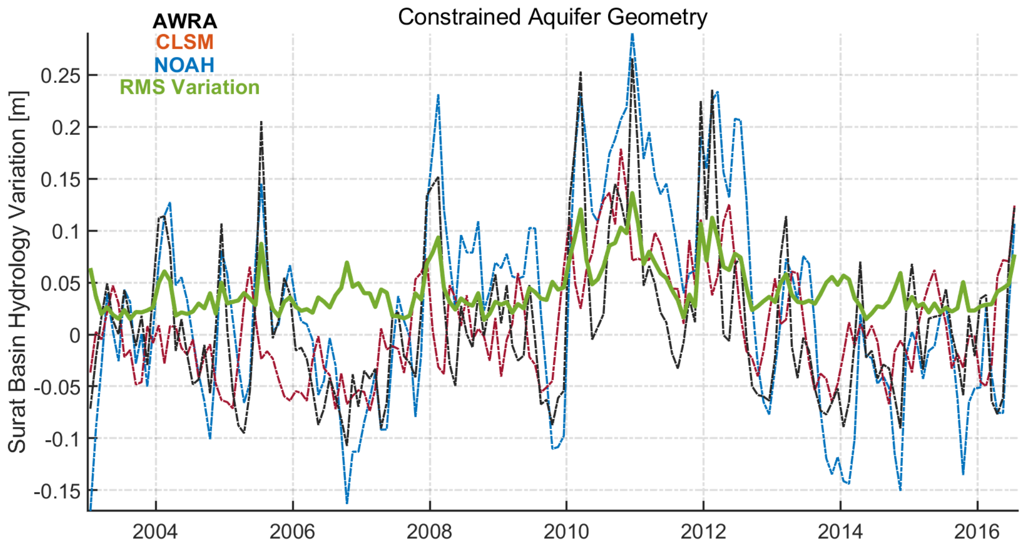

Figure 4*. Hydrology variation over Surat basin from 2003 to mid-2016. The blue dashed line derived from BOM/AWRA, red dashed line from GLDAS/CLSM, and blue dashed line from GLDAS/Noah. The bold green line shows the RMS variation among three hydrology models, and along with its increasing trend, it presents larger variation between 2010 and 2013.*

Limitations and Future works

Remote sensing using data from space gravity missions such as the Gravity Recovery and Climate Experiment (GRACE) (Tapley et al., 2004) provide broad-scale, accurate estimates of changes in TWS, but other components need to be removed before the groundwater signal can be identified. Errors in modelling/quantifying these other components map directly into the groundwater estimates and tend to dominate the error budget of the derived GWS.

The assimilation of remote sensing data – including TWS from space gravity and soil moisture from satellite missions such as SMOS (Soil Moisture Ocean Salinity, (Jacquette et al., 2010)), SMAP (Soil Moisture Active Passive, (Entekhabi et al., 2010)), Sentinel-1 (Geudtner, 2012) – provides an alternate means of deriving estimates of groundwater. Through this approach, the TWS derived from space gravity data can be partitioned into changes in water in different layers (e.g. shallow soil, root zone, groundwater, deep aquifers) ((Zaitchik et al., 2008), (Houborg et al., 2012), and (Tangdamrongsub et al., 2015)). The assimilation of GRACE data into the AWRA model yields more accurate estimates of groundwater across most of Australia (Tian et al., 2017) while the joint assimilation of GRACE TWS and soil moisture from the SMOS mission improved both soil moisture and groundwater estimates globally (Tian et al., 2019).

In future work we will follow the approach of Tian et al. (2017, 2019) and perform a joint assimilation of TWS from the ANU GRACE solution and soil moisture from SMOS data.

Appendix: list of data files

We provide a number of data files (in NetCDF format) which contain the information of groundwater estimates derived using each of the two mascon geometries and each of the three different hydrology model estimates of the non-groundwater hydrology contributions (Table 1):

Table A1. Filenames and descriptions of data files

File name	*Description*
Hydrology modelled values GLDAS-CLSM_SurfaceCatchmentGeometry.nc	• Soil, canopy and snow water content: GLDAS-CLSM (2.2) integrated over ANU primary mascons (February 2003 - December 2019) • mascon geometry: surface catchment
GLDAS-Noah_SurfaceCatchment.nc	• Soil, canopy and snow water content: GLDAS-Noah (2.1) integrated over ANU primary mascons (December 2002 - December 2019) • mascon geometry: surface catchment
BOM-AWRA_SurfaceCatchment.nc	• Soil water content: BOM-AWRA integrated over ANU primary mascons (December 2002 - December 2019) • mascon geometry: surface catchment.
BOM-AWRA_Aquifer.nc	• Soil water content: BOM-AWRA integrated over ANU primary mascons (December 2002 - December 2019) • mascon geometry: aquifer.
GLDAS-CLSM_Aquifer.nc	• Soil, canopy and snow water content: GLDAS-CLSM (2.2) integrated over ANU primary mascons (February 2003 - December 2019) • mascon geometry: aquifer.
GLDAS-Noah_Aquifer.nc	• Soil, canopy and snow water content: GLDAS-Noah (2.1) integrated over ANU primary mascons (December 2002 - December 2019) • mascon geometry: aquifer.
Total Water Storage values TWS_Australia_Aquifer.nc	• TWS solution: ANU • mascon geometry: aquifer
TWS_Australia_SurfaceCatchment.nc	• TWS solution: ANU • mascon geometry: surface catchments.
Groundwater storage change values GWS-AWRA_SurfaceCatchment.nc	• TWS solution: ANU surface catchment • Soil, canopy and snow water content: AWRA
	• TWS solution: ANU surface catchment

GWS-CLSM_SurfaceCatchment.nc	• Soil, canopy and snow water content: CLSM
GWS-Noah_SurfaceCatchment.nc	• TWS solution: ANU surface catchment • Soil, canopy and snow water content: Noah
GWS-AWRA_Aquifer.nc	• TWS solution: ANU aquifer • Soil, canopy and snow water content: AWRA
GWS-CLSM_Aquifer.nc	• TWS solution: ANU aquifer • Soil, canopy and snow water content: CLSM
GWS-Noah_Aquifer.nc	• TWS solution: ANU aquifer • Soil, canopy and snow water content: Noah

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