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Assessing drought vulnerability and water resource management in the Great Artesian Basin: insights from GRACE data and climate projections under varying emission scenarios

Razeghi, M[1]; Lyons, B[2]

[1]Rural Economies Centre of Excellence, University of Southern Queensland, mahdiyeh.razeghi@unisq.edu.au; [2]Rural Economies Centre of Excellence, University of Southern Queensland, ben.lyons@unisq.edu.au

Key words: Great Artesian Basin (GAB); Climate Change Projections; Total Water Storage-Drought Severity Index (TWS-DSI); Climate Scenarios; Remote Sensing.

Abstract:

This study examines the projected impacts of climate change on drought in the Great Artesian Basin (GAB), Australia, a vital groundwater resource for agriculture, industry, and ecosystems, which is increasingly vulnerable to prolonged droughts and climate variability. Using the Gravity Recovery and Climate Experiment (GRACE) satellite data and CMIP5/CMIP6 climate model simulations, the analysis, based on scenarios RCP2.6, RCP6.0, SSP126, and SSP370, reveals increasing drought severity, particularly under high-emission scenarios. The integration of GRACE-derived Total Water Storage (TWS) anomalies with climate projections enhances drought forecasting, highlighting critical drought hotspots in southern and central GAB regions. These findings underscore the importance of adaptive water management strategies, such as managed aquifer recharge, and the role of satellite-based observations in improving water resource sustainability in the face of climate change.

Introduction

Droughts are major natural hazards, especially in semi-arid and arid regions where they severely impact water resources, agriculture, and ecosystems. Understanding drought dynamics is crucial for managing groundwater systems, such as the Great Artesian Basin (GAB) in Australia, which is vulnerable to climate change and prolonged droughts (Rohde et al., 2017; Zhao et al., 2020). Effective water resource management relies on accurate drought forecasting, which is essential for addressing long-term drought risks. Recent advancements in remote sensing, notably through the Gravity Recovery and Climate Experiment (GRACE) satellite, have greatly improved monitoring of drought conditions. GRACE's ability to observe variations in Total Water Storage (TWS) is due to its high sensitivity to changes in the Earth's gravity field, which is directly influenced by changes in water mass. This enables GRACE to detect variations in water storage across both surface and groundwater reservoirs, offering unique insights into the spatial and temporal distribution of water resources during droughts, which cannot be captured through traditional ground-based methods such as streamflow measurements or groundwater monitoring alone (Tapley et al., 2004; Scanlon et al., 2012). GRACE data, with its global coverage and high sensitivity to changes in water storage, provides a comprehensive view of drought dynamics, particularly in regions with limited ground-based observation networks. Complementing this, climate models such as CMIP5 and CMIP6 project future temperature and precipitation patterns, offering insights into drought evolution under different scenarios (IPCC, 2014; O'Neill et al., 2016). This study leverages GRACE data to calibrate TWS estimates from CMIP5 and CMIP6 models, improving drought severity projections for the GAB across mid- and late-century periods. The integration of observational data with model projections enhances drought assessments, underscoring the importance of combining satellite data and climate models for effective water resource management in climate-sensitive regions (Scanlon et al., 2012; Zhao et al., 2020).

Case Study: The Great Artesian Basin (GAB)

The Great Artesian Basin (GAB) is one of the largest underground water reserves in the world, covering much of northeastern and central Australia. It provides vital water resources for agriculture, industry, and domestic use. The basin is crucial for Australia's water system, supporting local ecosystems and communities (Geoscience Australia, 2011). Figure 1(a) shows the GAB's geographic extent, covering Queensland, New South Wales, South Australia, and the Northern Territory, and highlighting key areas like Longreach, Broken Hill, and Birdsville. Understanding water storage dynamics in the GAB is critical, especially in the face of climate change and its impact on groundwater. Climate variability, including irregular rainfall patterns and extended dry spells, combined with rising temperatures, reduces the recharge of groundwater aquifers and increases evaporation, leading to more severe water scarcity and threatening the long-term sustainability of the GAB's water resources (Zhao et al., 2020). Satellite observations like GRACE play a key role in monitoring TWS changes in the GAB (Rodell et al., 2004). By integrating GRACE data with climate model projections from CMIP5 and CMIP6, we gain valuable insights into the basin's future water availability and drought risks under various climate scenarios (Collins et al., 2013; IPCC, 2014).

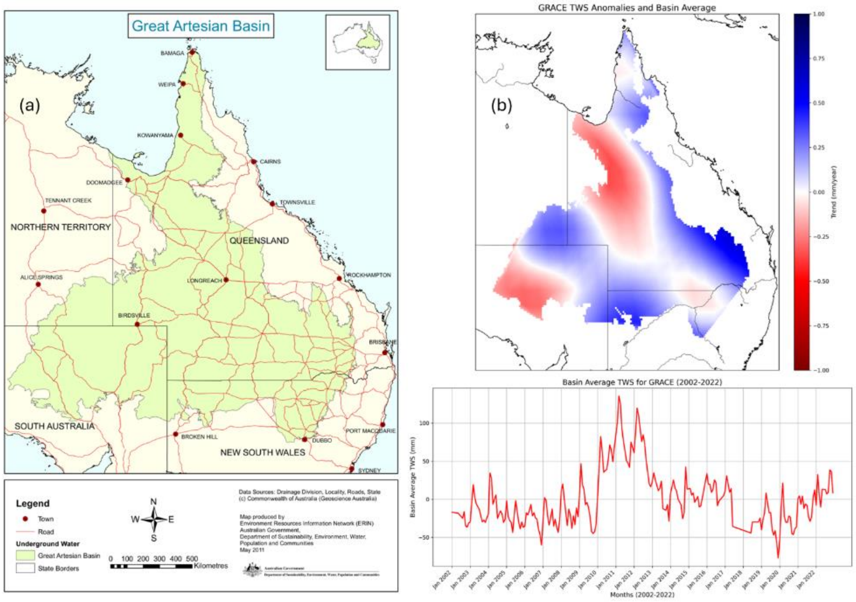

Figure 1.(a) Great Artesian Basin map, (b) Total water storage changes over GAB estimated by GRACE.

Data and Methodology

This study utilizes the Gravity Recovery and Climate Experiment (GRACE) satellite data (2002-2022) to analyse TWS anomalies in the GAB, Australia. The spatial resolution of GRACE data is approximately 250 km, providing global coverage with a focus on regional variations in water storage (Rodell et al., 2004; Tapley et al., 2004). GRACE measures changes in Earth's gravity field, providing critical insights into water storage variations over time (Rodell et al., 2004; Tapley et al., 2004). TWS anomalies are calculated by subtracting the climatological mean (2002-2022) from observed values, highlighting deviations from normal water storage conditions, which improves clarity and reduces repetition. The GRACE dataset, obtained from NASA's GRACE Data Portal, is widely used in hydrological and drought-related research. For future climate projections, we use data from CMIP5 and CMIP6 models, focusing on mid-century (2030-2059), and late-century projections (2070-2099). These models provide climate variables (e.g., precipitation and temperature) under emission scenarios: RCP2.6, RCP6.0 (CMIP5), and SSP126, SSP370 (CMIP6) (Collins et al., 2013; O'Neill et al., 2016). These scenarios were chosen because they represent a range of potential future climate outcomes, from low-emission pathways (RCP2.6, SSP126) to high-emission pathways (RCP6.0, SSP370), making them suitable for assessing the impact of various climate change scenarios on water resources and drought severity. TWS anomalies are calculated by subtracting the mean of monthly TWS values (2002-2022) from the observed values. To refine model projections, GRACE data were used to calibrate TWS seasonal cycles from CMIP5 and CMIP6 models. The calibration process involved adjusting the model outputs to better match the observed TWS anomalies from GRACE using statistical methods, such as the Root Mean Square Error (RMSE), which quantifies the difference between the model and observed values. Models with better alignment to GRACE data were weighted more heavily, based on their RMSE and structural diversity (Sanderson et al., 2017; Eyring et al., 2019). Drought severity is quantified using the Terrestrial Water Storage Drought Severity Index (TWS-DSI), which normalizes TWS anomalies by the standard deviation of monthly anomalies. The TWS-DSI indicates drought conditions based on a scale ranging from exceptionally wet to extremely dry. This method follows the World Meteorological Organization's classification guidelines, ensuring a globally consistent approach (WMO, 2012).

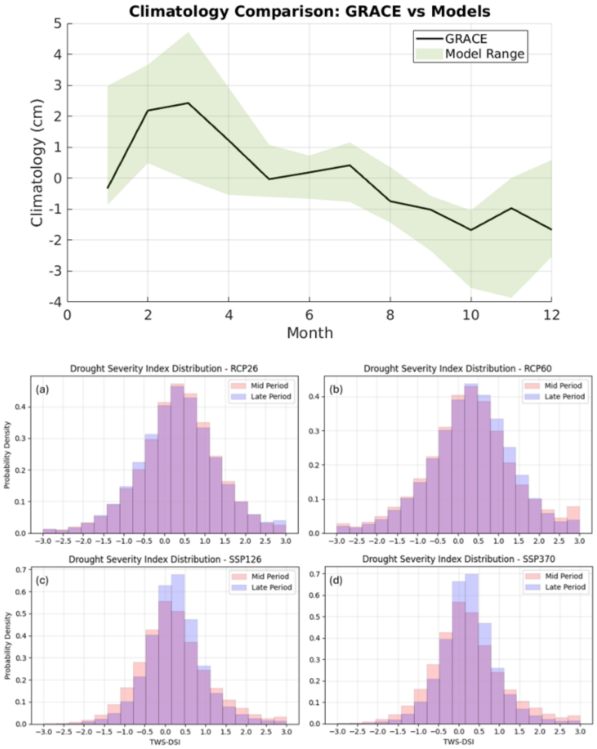

Figure 2. Top: climatology comparison between models and GRACE. Bottom: estimated drought index for mid and late century under different scenarios.

Results

GRACE TWS anomalies and basin average for the GAB (2002–2022): Figure 1(b) (top panel) shows TWS anomalies across the GAB from 2002 to 2022. Positive anomalies are observed in the northern regions, such as Weipa, while negative anomalies dominate southern areas like Coober Pedy, indicating varied water storage patterns across the basin. The lower panel of Figure 1(b) displays the basin-wide average TWS. Fluctuations include a significant positive anomaly during the La Niña event in 2010–2011 (Bureau of Meteorology, 2011), followed by a sharp decline of approximately 150% in mid-2019–2020, reflecting severe drought conditions (NSW Government Water, 2020).

Climatology comparison; GRACE vs models: The top panel of Figure 2 presents a climatological comparison between GRACE-derived TWS data and model outputs. GRACE data shows a clear seasonal cycle with higher water storage during the wet season (December to March) and lower values during the dry season (April to October). The models capture this general seasonal pattern but show discrepancies, particularly during the wet season, where some models overestimate TWS by up to 100%, likely due to overestimations in precipitation. These discrepancies highlight the need for model calibration using GRACE data to improve the accuracy of future projections.

Drought Severity Index (TWS-DSI) analysis for the GAB: The bottom panel of Figure 2 displays the probability density function (PDF) of the Drought Severity Index (TWS-DSI) for the GAB under different emission scenarios (RCP26, RCP60, SSP126, and SSP370) for both mid- and late-century periods. The PDF was derived by calculating the frequency distribution of TWS anomalies over the 2002–2022 period, categorizing the anomalies into drought severity levels ranging from -2 (extremely dry) to +2 (exceptionally wet). The histograms illustrate the distribution of drought severity under each emission scenario, with a shift toward more negative values indicating an increase in drought severity under higher emission pathways. For RCP2.6, the distribution remains relatively balanced, indicating near-normal drought conditions. However, under higher emissions scenarios like RCP6.0 and SSP370, the distribution shifts towards more negative values, signalling an increase in drought severity in the late-century period.

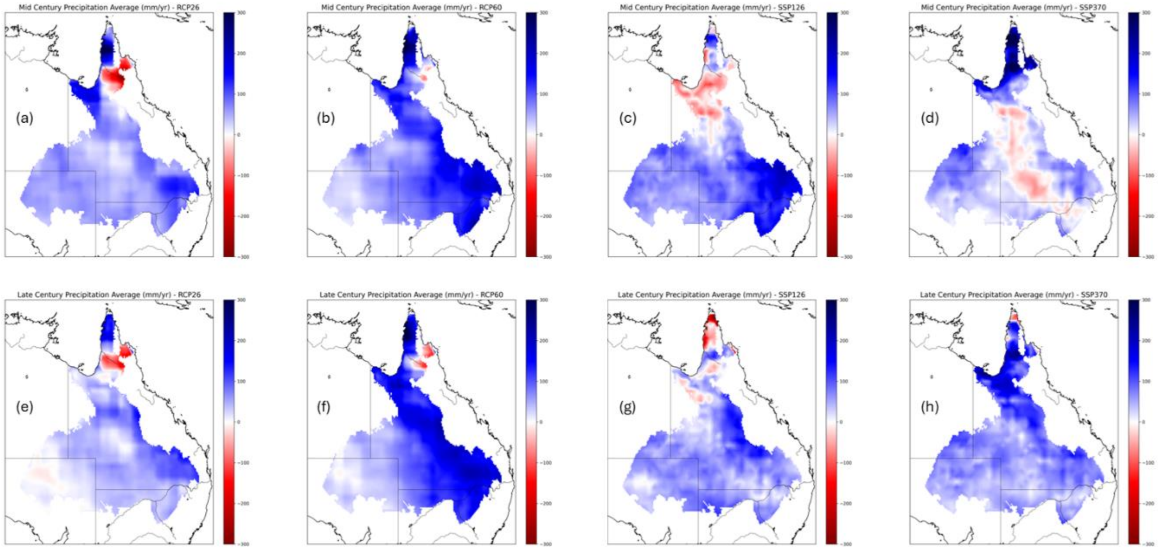

Figure 3. Precipitation projection for mid and late century under different scenarios.

Climate variables and drought index correlation: Figures 3 and 4 display mid- and late-century projections of precipitation and temperature changes across the GAB, with a historical baseline (1975–2005) removed for clearer quantification of changes. Figure 3 shows a general decrease in precipitation, particularly in South Australia and Broken Hill under high-emission scenarios (SSP370), with a 20-30% reduction in some regions. These trends align with more negative DSI values observed in Figure 2. Figure 4 shows a significant temperature increase, especially in southern regions, with areas like Birdsville expected to warm by up to 4°C under SSP370, which corresponds to a 15-20% increase in temperature. This temperature increase exacerbates evapotranspiration, while precipitation deficits in southern areas further intensify drought conditions. These trends align with IPCC (2021) projections and studies by van Dijk et al. (2013) and Crosbie et al. (2010), highlighting the increased vulnerability of groundwater and ecosystems in the GAB due to climate change. The results emphasize increasing drought severity under higher emission scenarios and more moderate impacts under lower emission pathways.

Discussion and Conclusion

This study examines the projected impacts of climate change on drought conditions in the Great Artesian Basin (GAB) using GRACE satellite data and CMIP climate model simulations. The findings reveal increased drought severity across all scenarios, with the highest risks under high-emission pathways like RCP6.0 and SSP370, especially in regions like South Australia. Even low-emission scenarios (RCP2.6, SSP126) show a gradual increase in drought intensity, particularly in areas such as Broken Hill and Weipa. Temperature increases of up to 4°C, especially in southern regions like Birdsville, correspond to an approximate 15-20% increase in temperature, exacerbating evapotranspiration, which could increase by 10-15%. Precipitation deficits in southern areas, with reductions of 20-30%, further intensify drought conditions. The results emphasize that higher emission scenarios lead to more frequent and severe droughts, while lower emission pathways, such as RCP2.6 and SSP126, help mitigate extreme drought conditions. These findings are consistent with studies by Thomas et al. (2014), which suggest that higher emission scenarios are likely to result in more severe and frequent drought events. The GAB's groundwater and ecosystems are increasingly vulnerable under high-emission pathways, as confirmed by earlier studies (van Dijk et al., 2013; Crosbie et al., 2010). GRACE data has been essential for validating model projections and refining drought indices. The discrepancies between GRACE data and model outputs, such as 100% overestimation of TWS during the wet season, highlight the need for model calibration to improve accuracy in future projections. To mitigate the projected impacts, adaptive water management strategies, such as managed aquifer recharge (MAR) and improved irrigation, are crucial. Scaling up MAR in the GAB will require investments in infrastructure, alongside better real-time monitoring of groundwater levels. Transitioning to low-emission pathways (RCP2.6, SSP126) can reduce the risks of extreme droughts by

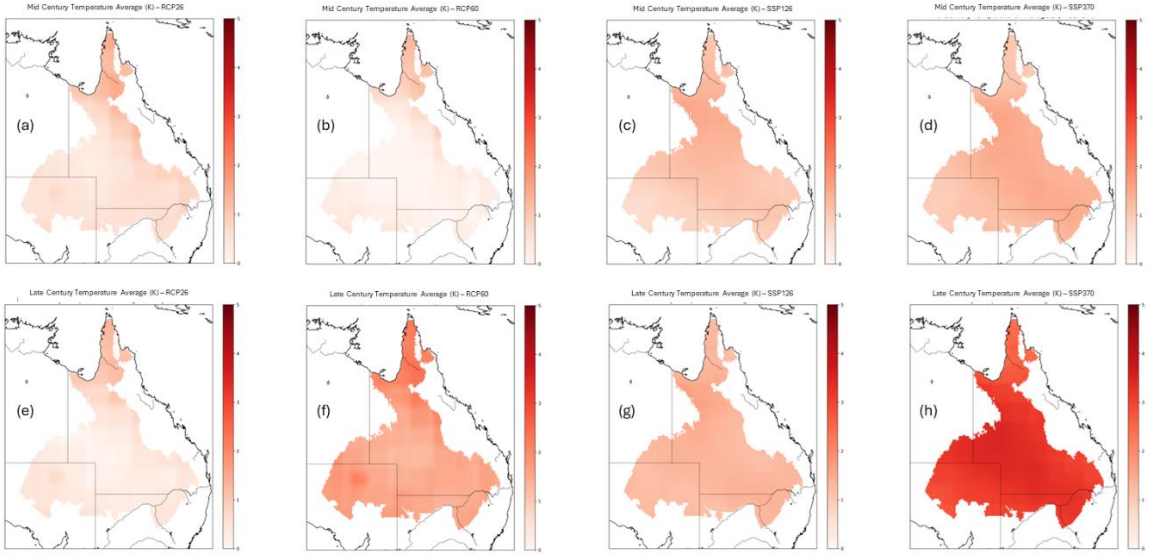

Figure 4. Temperature projection for mid and late century under different scenarios.

approximately 10-20% and support long-term resilience in the GAB. Integrating satellite-based monitoring into decision-making will enhance drought mitigation and water resource management, ensuring sustainable water use in the region under future climate change scenarios.

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