

Decreasing water resources in Southeastern U.S. as observed by the GRACE satellites

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ABSTRACT

Changing water quantities and location can be estimated using the Gravity Recovery and Climate Experiment (GRACE) satellites. By measuring differences in the Earth's gravity, the satellites provide monthly data on regional changes in the Earth's mass resulting from the movement of water. Studying the Southeast U.S., using the full record of the original GRACE satellites (2002–2016), a significant trend of declining water quantities appears in west-central Alabama, extending into eastern Mississippi. These findings confirm earlier research which indicates declining streamflow levels but develops this research further by estimating the amount lost as 11.6 km³. Considering the different terrestrial water storages by analyzing data from the National Climate Assessment – Land Data Assimilation System Noah 3.3 Version 2 (NCA-LDAS) indicates that the majority of this loss can be attributed to groundwater losses, a finding that is further confirmed by well records throughout the region.

Key words: GRACE, Groundwater, Remote sensing, Southeast U.S., Water resources

HIGHLIGHTS

- An area of decreasing water resources is found in Alabama-Mississippi.
- Irrigation using groundwater has increased during the study period.
- Losses identified are tied to declining groundwater levels in the region.

1. INTRODUCTION

Although Southeastern U.S. (hereafter 'the Southeast') may seem to have abundant water resources from a climatological perspective, enjoying a humid subtropical climate with precipitation originating from local convection and tropical storms in the summer, and frontal action in the winter, it has experienced multiple severe droughts during the last few decades as well as intermittent fast-onset flash droughts (Kunkel *et al.*, 2013; Praskievicz, 2019; Gavahi

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et al., 2020). The flash droughts, typically occurring during the warm season as a result of high temperatures in combination with low precipitation amounts (Otkin *et al.*, 2018), are particularly concerning for a region like the Southeast where agriculture and forestry constitute significant parts of the regional economy, and where riparian water-rights laws limit opportunities to use available surface water for irrigation, adding to the region's vulnerability (Engström *et al.*, 2020). Instead, groundwater is heavily used to meet the demands of irrigation and aquaculture as well as public supply (Tucker & Hargreaves, 2004; King *et al.*, 2012; U.S. Environmental Protection Agency, 2020).

Drought impacts in the Southeast range from declining aquifers, dry reservoirs, reduced stream flows, and degradation of ecosystems, to increasing interstate conflict, litigation, and federal intervention as states and cities compete for dwindling water supplies. The droughts and resulting water shortages have resulted in major legal conflicts affecting three states in the Southeast – Alabama, Florida, and Georgia, a conflict referred to as the ‘Tri-state water wars’ (Jordan, 2001). The conflict is centered on the Apalachicola-Chattahoochee-Flint River (ACF) basin, which runs on the border between Alabama and Georgia and crosses through Florida before draining into the Apalachicola Bay and the Gulf of Mexico (Figure 1). The ACF has experienced declining flows following increased consumption by the state of Georgia to satisfy the needs of the growing Atlanta metropolitan area, as well as agricultural irrigation needs of farmers in southern Georgia. Consequently, discharge of the lower portion (Florida) of the ACF basin has decreased, as well as discharge into the Apalachicola Bay, severely affecting ecosystems and associated businesses (Lancaster, 2017). Unrelated to drought, but fostered by the issue of groundwater management rights over a shared aquifer, is an interstate conflict in the Supreme Court of the United States between the state of Mississippi and the City of Memphis, Tennessee, due to extensive groundwater pumping in Memphis resulting in decreased surface discharge in Mississippi (Waldron & Larsen, 2015). In this original action, Mississippi sued Tennessee alleging the latter state was stealing its groundwater

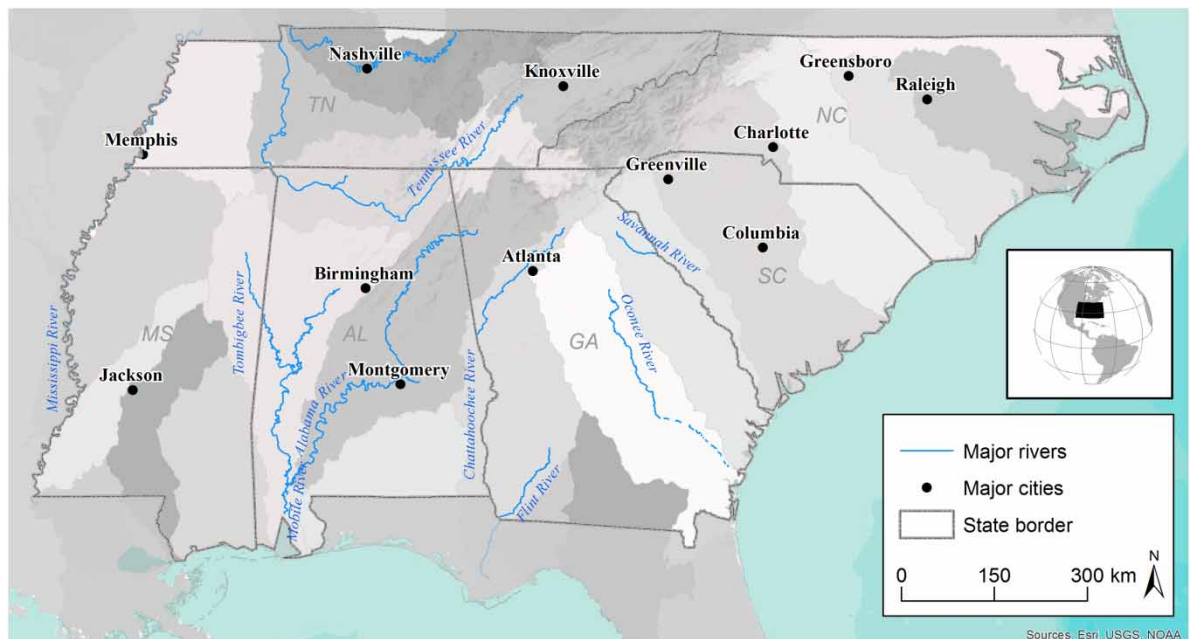


Fig. 1. | Overview of the study area. Major watersheds are shown in different shades of gray. The ACF basin, site of the interstate water conflict, is located on the border between Alabama and Georgia. The Tombigbee River flows from eastern Mississippi to western Alabama. The inset map indicates the relative location of the study area.

through pumping activities (*Mississippi v. Tennessee*, No. 220143, Complaint (U.S. filed June 6, 2014)). The Special Master appointed by the Court to hear the case recommended Mississippi's Complaint be dismissed without prejudice, but that Mississippi be permitted to amend its complaint to request equitable apportionment of the groundwater (*Mississippi v. Tennessee*, No. 220143, Report of the Special Master at 1 (U.S. Nov. 5, 2020)). The Special Master's decision found that the aquifer at issue is an interstate resource since the interconnected hydrogeological unit spans underneath multiple states (*Mississippi v. Tennessee*, No. 220143, Report of the Special Master at 11 (U.S. Nov. 5, 2020)). Lesser known water issues exist in other interstate river basins in the Southeast, such as the Tombigbee River basin that encompasses parts of western Alabama and eastern Mississippi (Figure 1). Extremely low streamflow was recorded in the basin's rivers during the flash drought of Fall 2016, threatening both ecological and economic values (Praskievicz *et al.*, 2018). The challenge of managing the region's water resources is exacerbated by the lack of well-developed, comprehensive water policy and management plans (including statewide water budgets, monitoring and permitting of surface water and groundwater withdrawals, and instream flow protection) in many Southeast states, including Alabama and Mississippi (Baer & Ingle, 2019).

Recent studies have indicated the Southeast is experiencing decreasing stream flow and groundwater storage (Richey *et al.*, 2015; Sadeghi *et al.*, 2019), and that droughts in the region might become more severe in the future (Keellings & Engström, 2019). The objective of this study is to analyze trends in total terrestrial water resources in the Southeast to (1) look for spatial patterns in terrestrial water storage (TWS) trends and (2) quantify any changes in the TWS. To conduct this analysis, data from the Gravity Recovery And Climate Experiment (GRACE) satellites from 2002 to 2016 is utilized. The joint US-German GRACE satellite mission is a useful tool in collecting data to quantify large-scale water movements. Since the launch of the program in March 2002, the GRACE twin satellites have measured differences in the Earth's gravitational force, resulting from a changed mass due to the movement of water, retreating glaciers, and geologic changes to the structure of the Earth's surface (Tapley *et al.*, 2004, 2019). The data is shared in the format of liquid water-equivalent thickness (cm) anomalies relative to the 2004–2009 base period. GRACE data can successfully be used to estimate changes in the total TWS, as well as in the respective pools (groundwater, ice sheets, etc.) on different time scales. Among the applications of the GRACE data is the estimation of changes in TWS in Australia following cool ENSO conditions (Boening *et al.*, 2012), groundwater depletion in India (Joshi *et al.*, 2020; Sarkar *et al.*, 2020), ice loss in Greenland (Velicogna *et al.*, 2014), and to inform climate models in data-sparse regions (Tapley *et al.*, 2019). In the U.S. GRACE data has primarily been utilized to estimate groundwater changes, such as in California (Famiglietti *et al.*, 2011), the Mississippi River basin (Rodell *et al.*, 2007), and the High Plains Aquifer (Brookfield *et al.*, 2018). As part of an international study, Richey *et al.* (2015) identified the Atlantic and Gulf Coastal Plains Aquifer as an aquifer that has experienced declining levels between 2003 and 2013. This aquifer underlies the southern part of this study's area of interest and extends along the coast of the Gulf of Mexico all the way to the Mexican border as well as northeast along the Atlantic coast of the U.S. up to New England. In a continental U.S.-scale study, Thomas & Famiglietti (2019) found mixed results and no field significance in Southeast.

The aim of this study is to assess changes in TWS in the Southeast. By focusing solely on this region, the goal is to provide more detailed findings of TWS changes and their causes than earlier studies which were conducted for larger geographic areas.

2. DATA AND METHODS

The study area for this project is the Southeast U.S., here defined as the six states of Alabama, Georgia, Mississippi, North Carolina, South Carolina, and Tennessee. This region was selected because there is reason to believe TWS would change over the study period because of several intense droughts and increasing use of groundwater resources. The study area roughly coincides with United States Geological Survey (USGS) Water Resource

Regions 3 (South Atlantic-Gulf) and 6 (Tennessee). Principal aquifers of the region include the Coastal Lowlands and Southeastern Coastal Plain aquifer systems (semi-consolidated sand), Piedmont and Blue Ridge aquifers (crystalline rock), Valley and Ridge aquifers (sandstone/carbonate), and Ordovician aquifers (carbonate).

To study the TWS of the Southeast U.S., monthly downscaled GRACE data with 0.5° spatial resolution is used (JPL GRACE Mascon Ocean, Ice, and Hydrology Equivalent Water Height Release 06 Coastal Resolution Improvement (CRI) Filtered Version 1.0) (Watkins *et al.*, 2015; Wiese *et al.*, 2018). Scaling factors are applied to minimize the discrepancies between the smoothed GRACE data and unfiltered land water-storage variations (Wiese *et al.*, 2016).

Although the GRACE satellites remained in operation until October 2017, the extent of the data used in this analysis has been limited to August 2002–July 2016, as the accelerometer of one of the GRACE satellites was turned off in August 2016, which resulted in subsequent degradation of the quality of the data observed after this date. The first observations in the record were excluded due to high uncertainty in the observations. For the overall trend analysis, August 2002–July 2016 was used allowing the time series to start and end at the same time of the water year, hence avoiding the impact of seasonality on the analysis.

The liquid water-equivalent thickness was transformed into volume (km³) to provide a more comprehensive measure of the quantity of water gained/lost. The non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975; Gilbert, 1987), commonly used for trend detection in hydrologic data (Hamed, 2008; Kalra *et al.*, 2008; Kumar *et al.*, 2009; Yeh *et al.*, 2015; Asoka *et al.*, 2017), is applied per pixel to the whole study area to search for any significant trend in TWS, while preserving the spatial variability of trends. This analysis was performed on the full data record as the limited length of the record made seasonal analysis unsuitable. To assess the linear rate of change in the trend identified, Sen's slope was computed (Sen, 1968). The total water volume change was calculated by multiplying the slope by the number of months included in the analysis.

To discern from what terrestrial water pool the decreasing water signal stems, there are different approaches. In arid regions, the groundwater signal is isolated by subtracting the surface water signal represented by variations of reservoir storage, while soil moisture and snow is negligible (Famiglietti *et al.*, 2011). In humid temperate regions, soil moisture and snow constitute a larger part of the hydrologic mass than the surface water (Rodell & Famiglietti, 2001; Rodell *et al.*, 2007; Getirana *et al.*, 2017; Brookfield *et al.*, 2018), and instead these measures are used to identify the groundwater signal. In the Southeast U.S., snow is rare, and instead soil moisture and surface water are used to isolate the groundwater signal. The atmospheric contribution to water mass changes observed by the GRACE satellites is negligible (Boening *et al.*, 2012).

In this paper, daily soil moisture (0–100 cm depth) and surface water with a 0.125° resolution from the National Climate Assessment – Land Data Assimilation System Noah 3.3 Version 2 (NCA-LDAS) (Jasinski *et al.*, 2018, 2019) were used to isolate the groundwater signal and elucidate from which TWS any significant changing signal originates (Equation (1)).

$$\Delta\text{Groundwater} = \Delta\text{Total terrestrial water storage} - \Delta\text{Surface water} - \Delta\text{Soil moisture} \quad (1)$$

3. RESULTS

Figure 2 shows the time series of TWS anomalies in the Southeast from August 2002 to July 2016. A clear pattern of seasonal variability can be seen, with the lowest annual anomaly occurring in September, marking the end of the hydrologic year. March is the month with the highest average water anomaly. The droughts of 2007–2008 and 2012 can easily be identified in the graph. This time series does not show any long-term trends for the study area

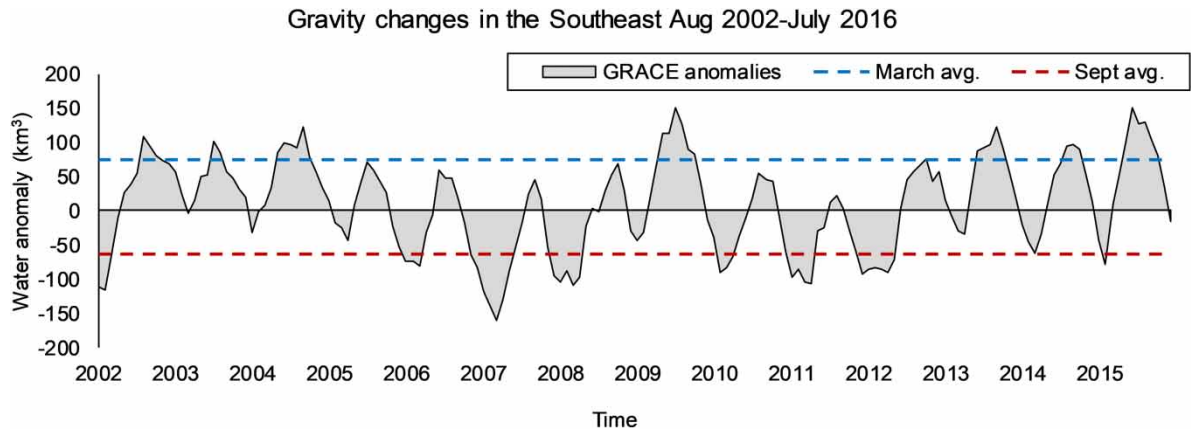


Fig. 2. | Time series of TWS anomalies in the Southeast, August 2002–July 2016. The blue dashed line shows the average anomaly for March (74.8 km^3), the month with the highest amount of water. The red dashed line marks the average for the month of September (-63.5 km^3) which has the lowest average anomaly and marks the end of the hydrologic year. The lowest observation in the record is October 2007 when the anomaly of the Southeast was -159.8 km^3 . Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wp.2021.039>.

as a whole, and although interannual patterns of variability might be discerned, identification and analysis of these are beyond the scope of this paper.

Upon looking for spatial patterns of gravitational trends in the Southeast U.S., an area extending from west-central Alabama to central Mississippi appears as having a significant negative trend in total TWS ($p < 0.05$) (Figure 3). Summarizing slopes of the long-term trend per pixel, for pixels with significant trends, results in a total loss estimate of 11.6 km^3 (5.92 km^3 in Alabama and 5.63 km^3 in Mississippi) over the study period (with an uncertainty range from -13.0 to -10.29 km^3). This translates to an average water level decrease of up to 0.9 cm/year , or a total of 13.5 cm for the 2002–2016 time period. An area of increased TWS appears in South Carolina and coastal Georgia, but this trend is not statistically significant.

Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly *et al.*, 2008; PRISM Climate Group, 2019) monthly gridded precipitation data was analyzed in search of trends that could explain the observed decrease. First, a Mann–Kendall test was applied to the precipitation data for the corresponding time period (August 2002–July 2016), but no significant trends were found. Next, the full PRISM record was analyzed (limited to August 1952–July 2016 to remove seasonal bias) for trends, recognizing that there might be a time lag between precipitation and terrestrial water response, particularly for groundwater. This analysis of the longer record showed that there has been a slight increase in precipitation in the region where the decrease has been observed (Figure 4).

This observed increase matches earlier research by Kunkel *et al.* (2013) that found a slight increase in annual precipitation in the Southeast and in Alabama in particular, a trend driven mainly by increased summer precipitation. The region is heavily influenced by different atmospheric drivers (teleconnections) (Kunkel *et al.*, 2013; Labosier & Quiring, 2013; Engström & Waylen, 2018) affecting the hydroclimatology on interannual scales, which complicates the identification of a trend. Many analyses therefore produce different trends depending on the length of the record analyzed, as well as the location of the observations, an inherent challenge in a region where the wet season precipitation originates from local convection, which varies greatly over time and space.

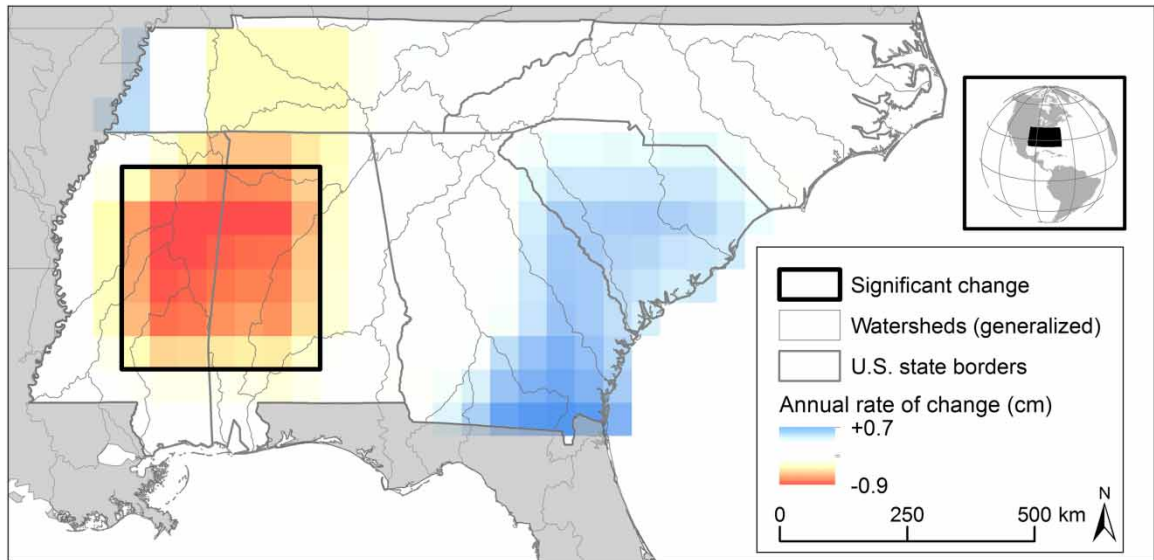


Fig. 3. | The study area includes the states of Alabama, Georgia, Mississippi, North Carolina, South Carolina, and Tennessee. A study of the full monthly GRACE record for the region identified an area spanning between central Alabama and Mississippi as having lost a total of 11.6 km^3 of water over the time period of 2002–2016. The data has been smoothed by a 3×3 low-pass filter for visualization purposes.

Figure 5 shows a time series (August 1, 2002–July 31, 2016) of anomalies of total TWS, soil moisture, and surface water for the region of decreased water sources. The data displays a clear seasonal signal, peaking in the spring. Soil moisture makes up the larger part of the variance observed, while the surface water signal is more limited, an observation that is aligned with findings from previous studies (Rodell *et al.*, 2007; Brookfield *et al.*, 2018). However, during periods of drought, such as 2007–2008, the groundwater level also decreases, and it needs a longer time to recover than the more shallow storages, which can be seen in early 2009 where soil and surface water shows a positive anomaly before the terrestrial storage does. A similar pattern of a lagged response can be seen in 2012–2013 following the drought of 2012.

Trends in well records for the states of Alabama (Geological Survey of Alabama, 2020) and Mississippi (National Ground-Water Monitoring Network, 2020) for the corresponding time period can be seen in Figure 6, confirming the finding that groundwater levels have decreased in large parts of the region. 26 of the 55 wells in Mississippi showed decreased water levels, while only two showed increased levels. In Alabama, 35 out of the 98 wells showed a decrease, and ten an increase.

Groundwater is the primary source of public water supply in the region, but USGS data shows that the extraction of groundwater for household use has declined over the study period. In particular, the pumping of groundwater for application on agricultural fields as well as filling of multiple aquaculture ponds result in increased evaporation rates and a net loss of water from the landscape, in comparison to water used for public supply, the majority of which is returned to the natural system after treatment.

To assess potential relationships between the observed decreases in TWS and patterns of groundwater usage, USGS water-use estimates (which are provided at the county level every 5 years) for 2000–2015 were examined (Hutson *et al.*, 2004; Dieter *et al.*, 2018). This timespan overlaps with the study period. All 83 counties in Alabama and Mississippi that experienced a decrease in TWS were included. In the aggregate, the affected counties

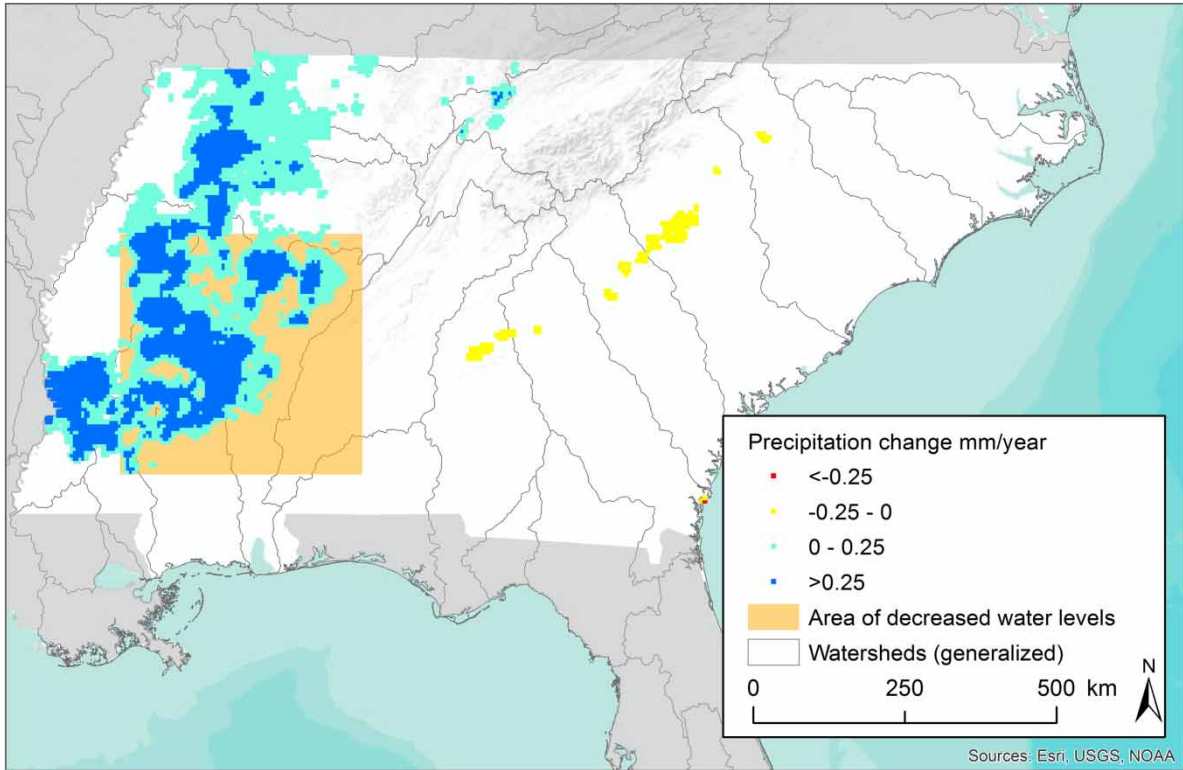


Fig. 4. | Map of significant changes in precipitation 1952–2016. Increase in precipitation is represented by blue hues, which mainly can be seen in the western half of the study area. Sporadic areas of precipitation decrease can be seen in the eastern half of the region. Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wp.2021.039>.

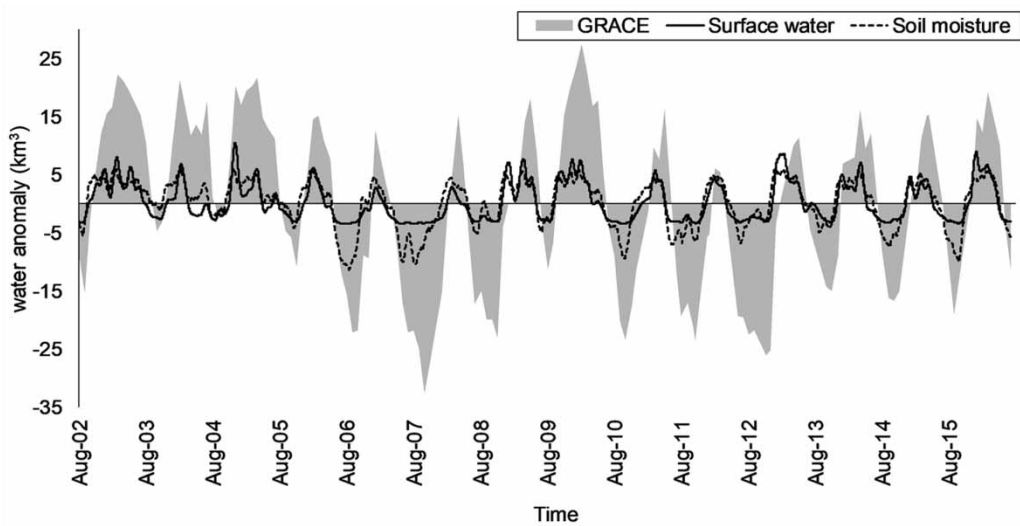


Fig. 5. | Time series of anomalies of total TWS (GRACE) and surface water and soil moisture (NCA-NLDAS). A 31-day moving window has been applied on the daily surface water and soil moisture data to remove noise and improve legibility.

experienced nearly a 4% decrease in estimated total groundwater use from 2000 to 2015, but over that same period, an increase of 29% in groundwater use for irrigation was estimated by the USGS. This finding is consistent with the idea that increased use of groundwater for irrigation may contribute to the observed loss of TWS in the region, even as total groundwater use remains constant or declines.

4. DISCUSSION AND CONCLUSION

In the current study, monthly TWS anomalies from the GRACE satellites are analyzed to look for trends in water quantity in the Southeast. Trends were analyzed at the pixel level (0.5° resolution) and a region on the border between Alabama and Mississippi emerged as having significant trends of declining water storage. The observed decrease is mirrored by *in situ* well records from the region, many of which show declining levels (Figure 6). No other part of the Southeast region showed any significant change in TWS.

It should also be noted that oil and natural gas are extracted from southern Alabama and Mississippi, as well as in a region stretching approximately from Tuscaloosa, Alabama, to just north of Starkville, Mississippi. There is no direct spatial overlap between the oil and gas fields, the area of decreased water levels as identified by the GRACE satellites, and the wells with decreased water levels, but an association between the fossil fuel extraction and decreased water resources cannot be ruled out. The source of the observed, although not statistically significant, increase in TWS in South Carolina and coastal Georgia is less obvious. The active hurricane season of 2016, which brought multiple storms to the area, does not impact the result, as the majority of the storms made landfall after the end of the time series included in this analysis (Hurricane Hermine and Tropical Storm Julia in September 2016, Hurricane Matthew in October 2016). Also, much of the south Atlantic coast has seen a decrease in tropical cyclone landfalls since 2012,

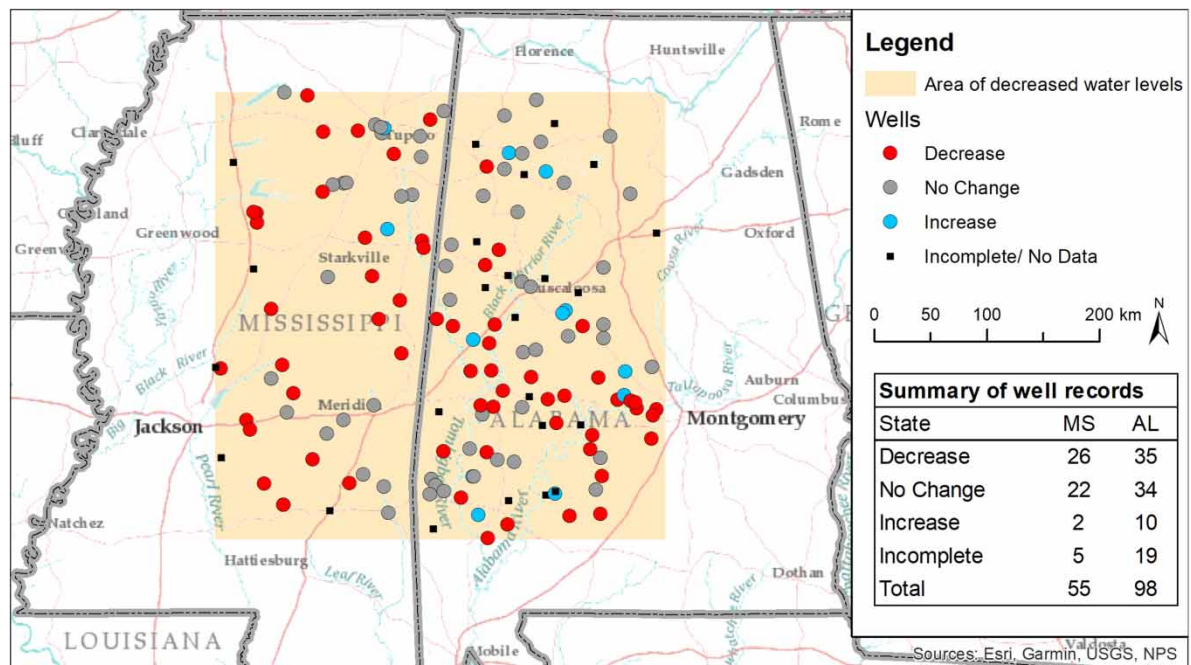


Fig. 6. | Map of well records in Mississippi and Alabama. A table to the right summarizes the result, showing a significant number of wells with decreasing water levels in both Mississippi (MS) and Alabama (AL). To be considered, the wells needed at least a 20-year record. Data from Geological Survey of Alabama (2020) and National Ground-Water Monitoring Network (2020).

a trend that has been associated with the long-term variability of sea surface temperatures and circulation in the Atlantic Ocean (Klotzbach *et al.*, 2015; Engström & Waylen, 2017; Kossin, 2017). It could be speculated that the water transfers from the ACF basin to farmers in southeast Georgia could be part of the explanation for the observed increase, but it cannot be concluded based on the analysis conducted here.

A thorough literature analysis was conducted to determine what TWSs should be included to isolate the groundwater signal. Earlier studies conducted in non-arid regions of the U.S. identified surface water as the smallest pool in the TWS (Rodell & Famiglietti, 2001), and surface water was completely excluded from more recent studies (Rodell *et al.*, 2007; Brookfield *et al.*, 2018).

Following the development of Land Data Assimilation Systems, like NCA-LDAS used in this study, estimations of surface water volumes are easier than before. Surface water estimations are included in this study and are not a negligible source of variability, but rather give a more balanced view of the source of the observed changes in the terrestrial system. The water balance presented in Equation (1) is generalized and does not account for mass variations associated with snow or biomass. This decision is based on the sparse snow cover in the region and that earlier studies have shown that variations in seasonal biomass are smaller than the uncertainty in the TWS observed by the GRACE satellites (Rodell *et al.*, 2005). The authors recognize that the simplification of the water balance equation (Equation (1)) brings uncertainty to the results.

Sources of uncertainty and error are inherently present in all datasets. In this study, there are a couple of notable sources of uncertainty. The GRACE data utilized in this study has been downscaled from its original 3° resolution to 0.5° to allow for more detailed regional analysis. Various downscaled GRACE datasets use different approaches to limit correlation errors in the new, smaller pixels, and a common challenge is over-smoothing where some geophysical signals 'fade out'. In the JPL GRACE Mascon Ocean, Ice, and Hydrology Equivalent Water Height Release 06 Coastal Resolution Improvement (CRI) Filtered Version 1.0, which is employed in this study, the smoothing is compensated for by adding scaling factors (Wiese *et al.*, 2016). NCA-LDAS is a hydrologic reanalysis dataset produced from land surface hydrologic modeling with multivariate assimilation of environmental data from numerous satellite platforms. The accuracy of the NCA-LDAS varies with parameter as well as geographically. In the Southeast, the root-mean-square error of runoff has been estimated to be 3.17 mm/year (Jasinski *et al.*, 2019), while the NCA-LDAS has proved superior in providing large-scale soil moisture data throughout the continental U.S. (Kumar *et al.*, 2019). The well records, many of which show declining levels (Figure 6), are neither evenly spaced, nor do they use the same aquifer. They are also monitored by different organizations with different routines regarding data collection and reporting. Uncertainties and errors in the data are unavoidable, particularly when working with datasets with large geographic extents that include observations from different sources that have been modified to represent a different geographic scale. The authors recognize these limitations but feel confident that they have used the best data currently available for the region of interest.

When assessing a hydrologic variable for temporal changes, the length of the record included in the analysis plays a crucial role, as the result is closely linked to variability in the record and trends and rates of change of a variable can be significantly different even as the time series is expanded or shortened by only a few years (Engström & Waylen, 2017). The time series used in this study is relatively short (14 years) and although the trend matches well with those identified using a shorter record (Famiglietti & Rodell, 2013), and available well records, these findings only represent trends that can be attributed to this time period. Further studies would be needed to determine if the trend observed here is part of a long-term trend of decreasing water resources in this region. Following the recent publication (Landerer, 2019) of gravitational data from the GRACE Follow-On mission (in orbit since May 2018), a continued monitoring of the TWS in the Southeast becomes viable. These data offer an opportunity to determine whether the region has recovered from the decrease observed in this study, or whether conditions have further deteriorated.

Long-term monitoring of water levels in west Alabama and eastern Mississippi, as shown from GRACE satellite data, has the potential to inform policymakers, stakeholders, and community groups of trends that will aid in constructive resolution of emerging environmental challenges at the intersection of law and policy. Armed with that information about long-term trends, they can make policy across (bilateral) and within (intrastate) state boundaries that allow them to provide resiliency and to thrive in a constantly changing water resource spectrum. A dependable supply of clean water is critical to economic development in the agricultural, manufacturing, extraction, transportation, and recreational sectors of the economies of both states. Groundwater fluctuations in Mississippi have already caused that state to look to surface water resources of the Tennessee–Tombigbee (Tenn–Tom) Waterway for potential water supply such as in the city of Corinth (Mitchell, 2013; Tennessee Valley Authority, 2018). The Tombigbee River contributes 40–50% of the flow into the Mobile River, the mouth of the fourth largest river basin in the U.S., which feeds Mobile Bay, the 12th largest port in the U.S. in 2019 (U.S. Army Corps of Engineers, 2019). The connected Tenn–Tom Waterway also directly impacts economic development of one-third of the counties in Alabama and is a significant economic driver in many northeastern Mississippi counties and communities. Long-term trends and the attendant implications can be viewed as an integrated water management regionalization – the coming together of communities that can be informed by data and enriched by data-driven policymaking.

Within the Tennessee–Tombigbee region of northwestern Alabama and northeastern Mississippi, it is believed that the essential water resources and transportation infrastructure exist to advance and sustain economic development while also protecting the water supplies and ecosystems of the region. However, a shared, science-based regional water resources management plan or framework does not currently exist that could guide economic development, decrease the potential for divergence of the states’ perspectives of how the water resources of the region could be used and sustained, and address potential drought-related scenarios. This situation necessitates the development of such a framework, and the timing is fortuitous for such a project.

The policy genesis of this study is recognition of the need for a comprehensive study of declining water levels in the region based on GRACE satellite data. Given the multitude of interests common to both states, the investigation described herein would provide science- and policy-based information to support appropriate and effective management decisions and help to avoid potential future interstate conflicts.

Analyzing TWS changes using GRACE data provides a ‘big picture’, and results are not necessarily useful for local water management (Alley & Konikow, 2015). Still, GRACE data provide higher temporal resolution than USGS’s water use reports that are issued every 5 years and greater spatial coverage than well monitoring. Hence, a combination of the datasets is recommended for the identification of regional hotspots of declining water resources.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (GRACE data: https://podaac.jpl.nasa.gov/dataset/TELLUS_GRACE_MASCON_CRI_GRID_RL06_V1. NCA-LDAS Noah-3.3 Land Surface Model L4 Trends 0.125 × 0.125 degree V2.0: https://disc.gsfc.nasa.gov/datasets/NCALDAS_NOAH0125_Trends_2.0/summary. National Groundwater Monitoring Network: <https://cida.usgs.gov/ngwmn/index.jsp>).

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