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# IMPLICATIONS OF LAND SUBSIDENCE DUE TO GROUNDWATER OVER-PUMPING: MONITORING METHODOLOGY USING GRACE DATA

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**ABSTRACT:** Groundwater over-pumping is a chief contributor to groundwater quality degradation and land subsidence. Expecting land subsidence is quite difficult, thus using satellite data to monitor such disaster is highly promising. This paper presents the use of Gravity Recovery and Climate Experiment data along with Global Land Data Assimilation System data to monitor and investigate land subsidence resulting from the impact of groundwater depletion in different regions throughout the world. The trend rates of groundwater depletion were spatiotemporally estimated to map and detect the occurring and prone regions of land subsidence. The groundwater storage changes exhibit a declining linear trend during the testing period (2002-2015) with a rate of 3.4 $km^3$/year at Missouri State in US. Based on the estimated linear tend of groundwater depletions, the method is validated at Missouri State by some exiting land subsidence such as sinkholes. Then, the approach is applied for the global and continental scales as example of US. The results also exhibit that the southern and some in the northern of US are the most prone regions for land subsidence. During the period 2009-2013, there was a great depletions and the results exhibit that mostly the abstractions from the North to the south of US and especially in the middle. Global estimates of groundwater storage changes also were conducted which can be used to estimate the groundwater depletion trends at any region throughout the world. These analyses could be helpful for monitoring and assessment of land subsidence in regions where subsidence impacts are great.

*Keywords: Land subsidence, GRACE, GLDAS, Groundwater storage anomalies, Groundwater depletion, USA*

## 1. INTRODUCTION

Groundwater level variations are the most dominant cause of land subsidence. Groundwater over-drafting can lead to a number of adverse consequences, such as saltwater intrusion or groundwater quality degradation; streamflow depletion; environmental degradation; and land subsidence. According to the U.S. Geological Survey, land subsidence is a phenomenon found across the United States, affecting more than 17,000 square miles in 45 states [1]. Most subsidence in the US is attributed to groundwater exploitation, and the increasing development of land and water resources portends exacerbating existing land-subsidence issues and initiating new ones [1].

Land subsidence due to the over-pumping was observed in many groundwater aquifers around the world (e.g. [2-3]). It has existed at different rates that can extremely exceed Sea Level Rise (SLR), global present mean: 0.32 cm yr−1, [4]. Interferometric Synthetic Aperture Radar (InSAR) measure a phase shift of radar waves backscattered by the Earth's surface between two satellite passes, a component of which can be a direct observation of land surface deformation during the elapsed time between the passes. Using InSAR data to investigate land subsidence resulting from groundwater extraction (e.g., [5], [6], [7] have been enabled by the increasing data availability since 1992 from SAR instruments working over different time periods and imaging at a variety of wavelengths.

An example of oil-field subsidence is the Welmington oil field in Los Angeles County, California, which has experienced 9 m of subsidence [8]. Land subsidence causes usually serious economic and social problems in many regions throughout the world. Scientists and engineers conducting several studies and plans for industrial complexes, urban developments, water supply systems, and natural resource extractions need to know about the potential hazards, costs, and socio-environmental impacts caused by land subsidence [9]. Existing of land subsidence caused by groundwater extraction has addressed at many regions over the world [10] and in Sweden and Norway and probably in other glaciated areas of similar geologic and hydrologic environments [2].

In general, remote sensing techniques have recently been used in many studies such as estimating soil moisture in the root zone and ground displacement monitoring [11], land applications [12], managing salinization [13], soil salinity mapping [14], and high accuracy road positioning [15]. GPS as one of the most crucial remote sensing techniques has been used in different fields, including integrating GPS with barometry [16], dynamic deformation monitoring of tall structures [17], and hydrographic applications [18].

Land subsidence causes disorders in sustainable water management and critical civilian infrastructure (e.g., buildings, roads, railways, canals, aqueducts and pipelines) [3]. Subsidence occurs naturally and anthropogenically, where the principal causes are aquifer-system compaction, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost [19].. In order to study land subsidence, both the geologic setting and the development of the land and natural resources (e.g., water, oil and gas) are required to be considered. The potentiality of subsidence is greater where some of these geologic processes are affected by man's activities including excavation, loading, or extraction of subsurface fluids (e.g., groundwater extraction). Some studies have been done based on understanding the soil physical properties at specific land subsidence site [20] and estimating $CO_2$ emission and land subsidence to evaluate the impact of drainage on food crops and various forest scenarios [21].

Subsidence resulting from sinkhole collapse is occurring in areas which underlain by water-soluble rocks such as carbonate rocks [22], The term ‘‘karst’’ has been widened to include features that reflect surficial dissolution processes (epigenic karst, and hypogenic karst) which lead to increase land subsidence potentiality [23]. Land subsidence is an important and critical environment issue. Over-pumping is not sustainable in the long term, leading to a number of adverse consequences, such as groundwater quality degradation and land subsidence. Lack of observational data makes land subsidence, sinkhole collapse and karst subsidence, a great challenging hazards as a global risk which should be addressed. Therefore, attempting to utilize the freely available global datasets to assess the land subsidence in regional or global scales is quite important as a first stage for further comprehensive analysis over local scales. Gravity Recovery and Climate Experiment (GRACE) data [24] in terms of groundwater applications have been applied in many regions over the world such as examine the potential of GRACE data to monitor groundwater storage changes [25] or comparing groundwater satellite derived and groundwater based observation derived showing a reasonable matching trends [25]. Therefore, the main purpose of this paper is to demonstrate a method using GRACE remote sensing data and Global Land Data Assimilation System to monitor and investigate land subsidence resulting from the impact of groundwater depletion in the United States and the world to support management and mitigation for land subsidence and water resources depletion [26].

## 2. STUDY REGIONS

The method was applied at three scales as follows: local scale as the State of Missouri (USA), regional scale as in the United States as shown in Fig. 1, then the global scale. In 1970 and 2007, the Missouri Department of Natural Resources examined more than 160 incidents of collapse sinkholes reported by the public. Most of these collapses were small, less than 10 feet in diameter and 10 feet deep, but some were large [27].

## 3. METHODOLOGY

In this paper, we used GRACE data to infer land subsidence resulting from the impact of groundwater depletion at different spatial scales: Missouri (USA), USA and the world. Changes in groundwater storage were estimated from the residual of GRACE terrestrial water storage (TWS) anomalies [29] and components of TWS, such as surface water, soil moisture storage, snow water equivalent, and canopy water estimated using Global Land Data Assimilation System (GLDAS). TWS anomalies can be represented as:

$$\Delta S_{TWS} = \Delta S_{SW} + \Delta S_{SM} + \Delta S_{GW} + \Delta S_{cpy} + \Delta S_{SWE} \quad (1)$$

where, ΔS: is (the monthly, seasonal, or annual changes), SW: is surface water, SM: is soil moisture, cpy: Canopy water, SWE: Snow water equivalent, and GW is groundwater storage.

Changes in groundwater storage can be represented by rearranging Eq. (2) as:

$$\Delta S_{GW} = \Delta S_{TWS} - (\Delta S_{SW} + \Delta S_{SM} + \Delta S_{cpy} + \Delta S_{SWE}) \quad (2)$$

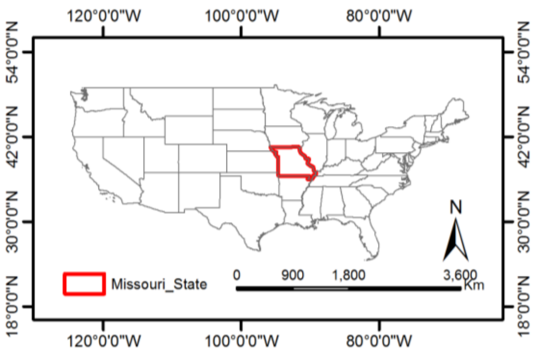


Fig.1 Location map of Missouri State in USA

The 1° x 1° spatial and monthly temporal resolutions of GRACE TWS data and GLDAS data were averaged to calculate annual values within the time period Oct. 2002- Sept. 2015 (Water Years

2003-15). Then, surface water, soil moisture storage, snow water equivalent, and canopy water anomalies were computed by removing the mean value over the time period (Oct. 2002- Sept. 2015) from the monthly soil moisture values. The potential for land subsidence was evaluated based on groundwater depletion trends estimated from linear trends in the time series of groundwater storage anomalies. The adopted approach has been applied in many previous studies with reasonable potentiality to estimate the ground water storage changes [24,30-34]. Distribution maps showing land subsidence prone areas were validated by the observed data.

## 4. RESULTS AND DISCUSSIONS

### 4.1 Case Study 1: Missouri (USA)

Missouri is vulnerable to sinkholes because it is underlain by thick, carbonate rock [35]. Hydrographs and distribution maps of groundwater storage and groundwater level anomalies were developed for Missouri (USA) (Figs. 2 and 3). The groundwater storage changes exhibit a declining linear trend during this time period (2002-2015) with a rate of 3.4 km3/year over the whole area. The estimated declining rate of groundwater storage anomalies (Fig. 3(a)) show a reasonable agreement with the observed groundwater levels declining trend by USGS (Fig. 3(b)). Groundwater wells in the aquifer have experienced water level declines in recent years as shown in Washington County, Missouri (Fig. 3(b)). This could be the reason for subsidence in this area. We found a declining trend of groundwater storage anomalies of about 0.19 cm/year for the time period 2002-2015, (Fig. 2). In addition there are great storage depressions represented in three stages from 2002-2005 (Fig. 4(a)), 2007-2010 (Fig. 4(b)), and 2011-2015 (Fig. 4(c)).

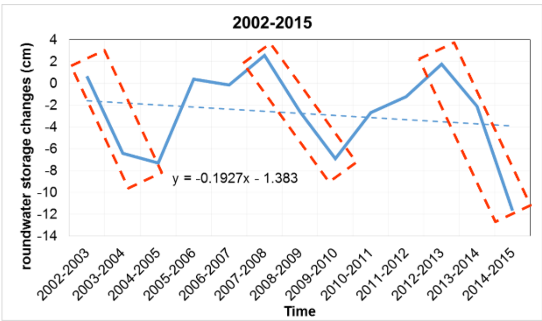


Fig. 2 Time series of groundwater storage anomalies from 2002-2015 for Missouri (USA) showing three declining time periods.

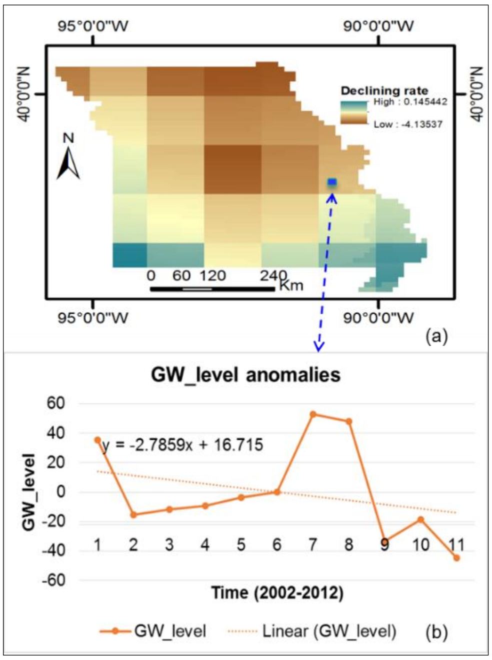


Fig. 3 Spatial distribution map of declining trend (linear slope) of groundwater storage anomalies from 2002-2015 for Missouri (USA) (a), and observed groundwater level from 2002-2012 showing a declining water level at Washington County, Missouri (USA) (b ).

The most prone regions for land subsidence due to groundwater depletion are observed in the northern and western part of Missouri (Fig. 4a) during the time period 2002-2005, in the northern parts during the time period 2006-2011 (Fig. 4b), in the southern part during the time period of 2011-2015 (Fig. 4c). In 2006 some sinkhole occurred in the southwest Missouri town of Nixa [36] which follows the first declining stage from 2002-2005. The prone regions of land subsidence show that the estimated results almost coincide with the observed sinkholes (Fig. 4a).

The largest known sinkhole in Missouri encompasses about 700 acres in Boone County as stated by [37]. In comparison with the present results of land subsidence risk map (Fig. 4b), the area around Boone County is located in the high risk zone for subsidence. Additionally, it was observed that a sinkhole occurred at the Rock Golf course near the resort town of Branson, Missouri, in May 2015, at the end of last declining period from 2011-2015. The risk map during this time period shows that the most prone regions for land subsidence occur at the same location (Fig. 4c).

Based on these relations between groundwater storage depletions and sinkhole occurrence, the proposed methodology is reasonably suited to monitor the prone regions for land subsidence at the study area.

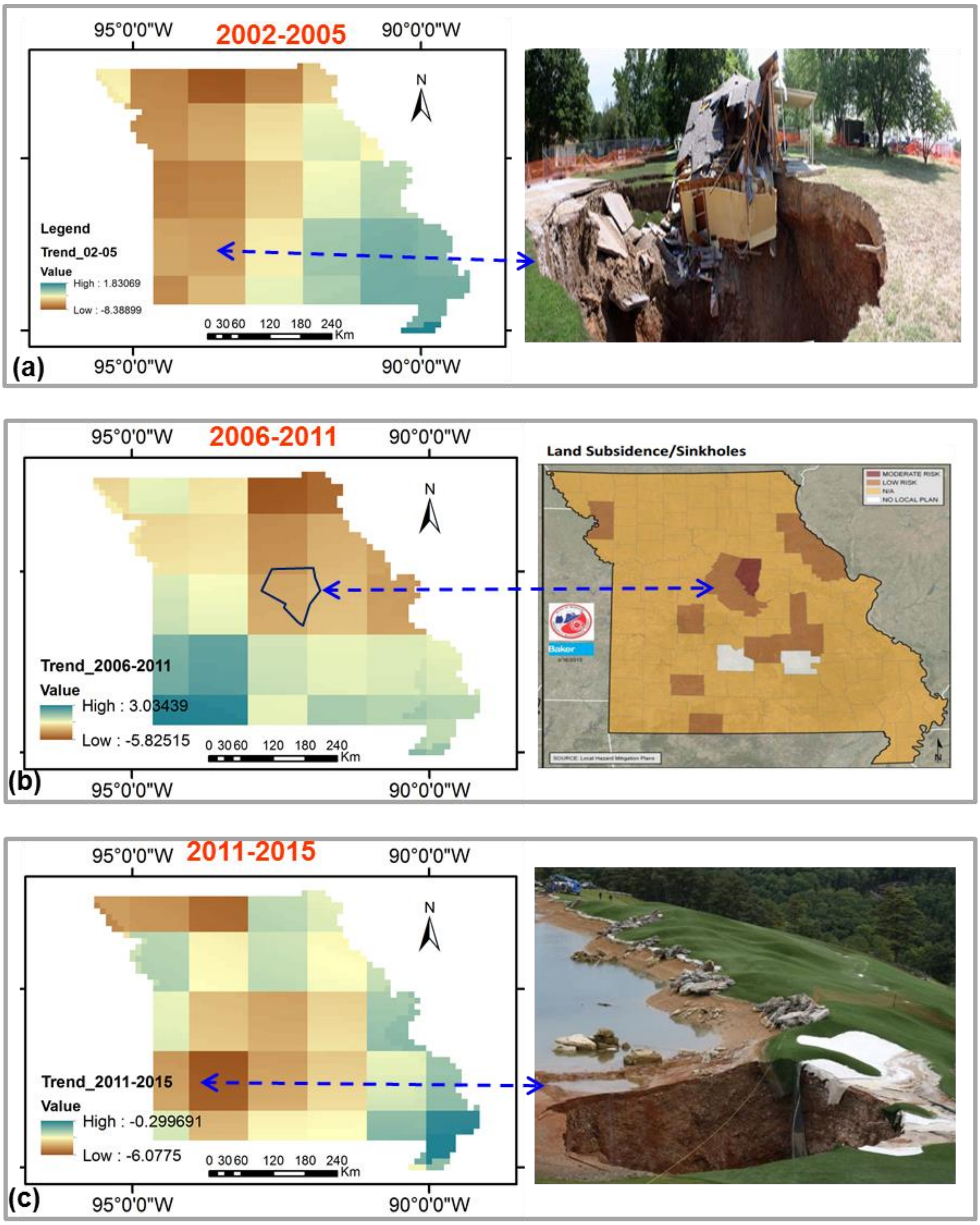


Fig. 4 Distribution maps of land subsidence risk based on the declining trends rate of groundwater anomalies from 2002-2015 for Missouri (USA) show three stages of depletion as follows: (a) land subsidence risk map based on the trends of groundwater depletions from 2002-2005 (left) and observed sinkhole collapse that occurred in 2006 in the southwest Missouri town of Nixa (right), (b) land subsidence risk map based on the declining rate within the time period 2006-2011 (left) and observed land subsidence/sinkhole observed by USGS [35] (right), and (c) land subsidence risk map based on the trends of groundwater depletions from 2011-2015 (left) and observed sinkhole collapse that occurred in 2015 at the Rock Golf course near the resort town of Branson, Missouri (right).

### 4.2 Case Study 2: United States

Total water storage changes for the period 2002-2015 were estimated over the US and we found that the most storage depleted regions during this period are located in the South, southeastern, and some parts in the northcentral continental US (Fig. 5).

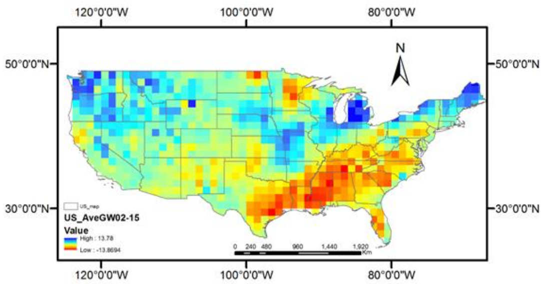


Fig. 5 Spatial distribution map of total average of groundwater storage anomalies from 2002-2015 in the continental United States.

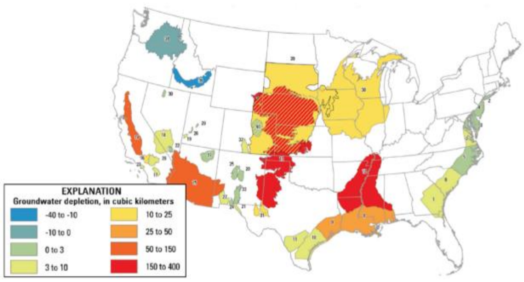


Fig. 6 Groundwater depletion estimates for continental US [38].

Groundwater depletion estimates were estimated using a synthesis of studies for the major US aquifers from 1900 to 2008 [38] (Fig. 6). The present results highlight the groundwater depletion Mississippi Aquifer exhibit which agree with [38] estimates.

The land subsidence potential maps were also developed based on the groundwater anomalies declining trends during the time period from 2002-2015 (Fig. 7). The southern and some in the northern of US are the most prone regions for land subsidence based on estimation of depletion trends of groundwater. During the time period from 2009-2013, there was a great depletions and the results exhibit that mostly the abstractions from the North to the south of US and especially in the middle.

### 4.3 Case Study 3: World Analysis

The average annual groundwater storage anomalies throughout the world were estimated showing the groundwater depletions (Fig. 8). The depletion trends of groundwater anomalies can be estimated from this map for any regions over the world to indicate for the global land subsidence.

## 5. CONCLUSION

In the present study, groundwater storage anomalies estimated from GRACE/GLDAS data were used to monitor and detect the prone regions for land subsidence due to over-pumping. The

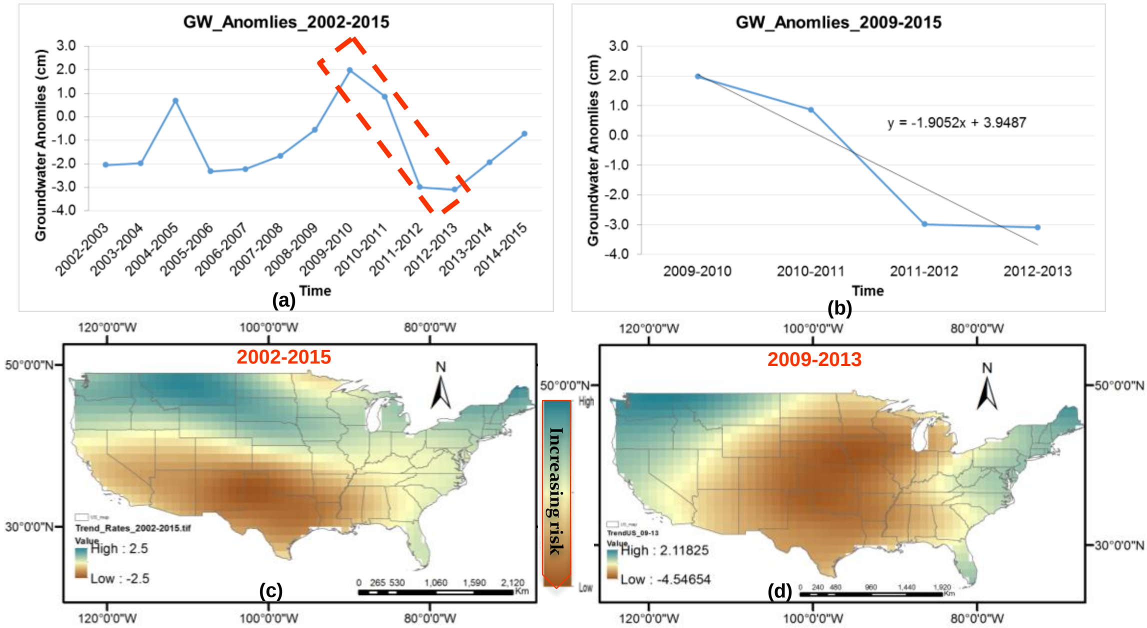


Fig. 7 Time series of groundwater storage anomalies from 2002-2015 (a) and from 2009-2013 (b). Spatial distribution map of depletion linear trends indicating for land subsidence potentiality from 2002-2015 (c), and from 2009-2013 (d) at the continental US.

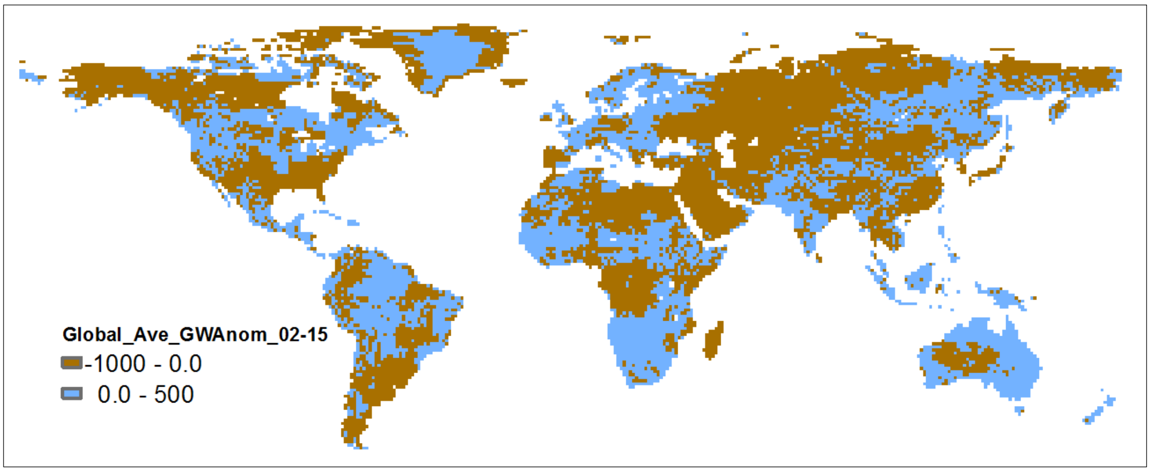


Fig. 8 Spatial distribution map of total average of annual groundwater storage anomalies from 2002-2015 throughout the world (blue (positive) color indicates for increasing in the groundwater storage, and brown (negative) color indicates for decreasing of the groundwater storage).

prone regions of land subsidence were monitored and detected based on the equivalent groundwater storage changes. Application and validation of the results have been conducted for the State of Missouri (USA) and the United States. The groundwater storage changes show a declining trend rate of 3.4 $km^3$/year over Missouri State during the period of (2002-2015). Global estimates of groundwater storage changes also were made which can be used to estimate the groundwater trends at any region throughout the world. Mapping and identifying of subsidence prone regions have been done using the declining groundwater storage rate to support implementing effective subsidence-monitoring programs.

The merit of this research is that long-term management strategies to minimize the land subsidence resulting from the groundwater depletions could be addressed. This could be helpful for monitoring and assessment of land subsidence in ungauged regions all over the world.

Further research could include analysis of the identified groundwater depletion areas and subsidence prone areas using Differential Interferometric Synthetic Aperture Radar (D-InSAR) techniques. The maps produced in this study can be used as a guide for any detailed and local studies of land subsidence due to the groundwater depletion. Future validation are needed using other methodologies such as InSAR data at several sites over the world as stated by [24] that InSAR can be used to partially overcome limitations of GRACE resolution.

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