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A review of satellite-based monitoring of groundwater storage changes and depletion consequences

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Abstract. Groundwater demand is increasing due to global population growth, climate change and rapid urbanization, however, poor planning and over-exploitation are leading to rapid depletion of groundwater, which in turn causes adverse impacts such as land subsidence, soil salinization and water quality deterioration. Groundwater storage (GWS) monitoring is essential to the sustainable management of regional water resources and the prevention of environmental and social issues associated with depleted groundwater resources. Conventional groundwater observation is primarily conducted through groundwater well-level measurements, which requires a lot of time and effort, and is insufficient to accurately reflect GWS changes regionally and monitor large-scale groundwater level changes. The availability of various satellite data makes it easier to study groundwater information effectively. The aim of this paper is to first review the seriousness of groundwater depletion, every year, 15% to 25% of the total global groundwater extraction is overexploited. Then, based on satellite geodetic technologies such as Gravity Restoration and Climate Experiment (GRACE), GRACE Follow-On, Sentinel-1, and Global Navigation Satellite System (GNSS), the basic principles of GWS monitoring are expounded. The reliability of the monitoring results was analyzed through the literature summary, showing that the results were basically consistent with the trends reflected by the measured groundwater samples, and the statistical significance of quantitative comparisons was higher than 0.65. The impact of the consequences of groundwater depletion also deserves our attention. This paper combined with multi-source satellite and tidal data, etc., the feasible research methods are discussed for a series of adverse consequences caused by groundwater depletion.

1. Introduction

A total of 10.6 million km3 of liquid freshwater exist in the world, of which 99% is groundwater[1]. In residential life, industry and agriculture, groundwater is inseparable. At present, groundwater supplies half of the world's residential water, and the industrial and agricultural groundwater accounts for 40% and 25% respectively. Although it is so significant, however, in many places the management of groundwater is not perfect, or even abused. Improper planning and over-exploitation of groundwater have caused groundwater levels to drop or even deplete. Not only are major threats to the efficient utilization of freshwater sources being raised [2], but also leads to adverse consequences such as l surface sinking, seawater intrusion, etc. [3]. In order to maintain the efficient exploitation of area water sources and prevent environmental and human issues associated with groundwater depletion, it is very urgent to monitor the dynamic changes of GWS [4].

The most representative GWS change monitoring methods include groundwater level fluctuation method (WTF), hydrological model [5], groundwater flow model [6] and satellite gravity measurement [7]. However, the use of monitoring wells to measure groundwater levels requires a sufficient number of monitoring points and a reasonable distribution. Therefore, during the early stages of selection and layout, a great deal of work needs to be done. Even so, it is challenging to properly represent the changes in GWS regionally. Inaccurate observation results are often the result of hydrological models that ignore the complexity of hydrological processes. Satellite gravimetry is increasingly favored by researchers.

With unprecedented precision, GRACE started collecting data on the gravity field's changes since its launch in 2002. GWS anomalies (GWSA) can be derived from changes in terrestrial water storage (TWSA) using water balance methods, or can be calculated in conjunction with land surface models (LSM) and GRACE data. InSAR technology provides a new perspective on global groundwater monitoring systems. According to previous studies, InSAR-based deformation can estimate groundwater level (GWL) changes [8], which has the benefits of wide coverage, high accuracy, and high resolution. With Sentinel-1 imagery becoming more accessible, basin-scale land subsidence data can now be obtained and groundwater levels can be further studied. A measurement of the vertical displacement using the Global Navigation Satellite System (GNSS) are used to generate TWSA estimates but requires high station densities and minimal contamination from non-hydrographic sources of deformation [9]. By combining InSAR, GNSS and GRACE, it is possible to produce more accurate estimates of TWSA [10].

The depletion of groundwater not only threatens the sustainability of water supplies, but also causes Vertical Land Motion (VLM), soil salinization, seawater intrusion, and relative sea level rise. Increasing groundwater extraction has become a significant factor in land subsidence. Globally, the over pumping of groundwater has caused considerable VLM in more than 200 cities [11]. Coastal aquifers are affected by seawater intrusion, which is one of the main sources of pollution. Salinity levels surpassing safe drinking water limits are a critical issue to address. As a result of VLM and climate-induced SLR, the RSLR around the world's coasts has increased roughly four times faster than the published worldwide SLR calculations [12]. Various adverse consequences caused by groundwater depletion require our high attention.

In this article, the purpose is to review the literature to understand the serious situation of groundwater depletion in various locations. Review the current GWS monitoring methods based on various satellite data and evaluate their accuracy. At the same time, there are also concerns about the consequences of groundwater depletion. We present feasible research methods for a series of adverse consequences of groundwater depletion using multi-source satellite and tidal data.

2. Research Methodology

This study adopts a descriptive method to carry out a literature review, and conducts a preliminary review of domestic and foreign studies on groundwater storage and related consequences using satellite technology, and puts forward the following research questions:

- What is the status of groundwater depletion around the world?
- What are the existing methods for studying groundwater storage and how accurate are they?
- How to combine advanced satellite technology to assess the consequences of groundwater depletion?

Search peer papers from 2010 to 2023 through major search engines such as Web of Science, ScienceDirect, Google Scholar, SpringerLink, etc. The journals cited in this paper include "nature", "Journal of Hydrology", "Groundwater Sustainability", "Environmental Research Letters", "Geophysical Journal International", "Geodesy and Geodynamics", "Remote Sensing", etc. According to the identified 3 literature review questions, they searched separately, and then checked the titles and contents of the articles to screen more than 50 references.

3. Result and Discussion

3.1. Status of groundwater exploitation

Groundwater is an important natural resource. When groundwater extraction exceeds recharge, groundwater storage decreases. While climate may play a role in this process, the main reason is human overexploitation. Every year, 15% to 25% of the total global groundwater extraction is overexploited. Global freshwater withdrawals are dominated by Asia (64.5%).

Despite China's 20% population share, its freshwater resources account for only 5% to 7% of the world's total [13]. Many areas make up for the increasing demand for water by exploiting groundwater. As a result of the rapid decline in groundwater reserves in some parts of China, groundwater scarcity has become detrimental to the nation's water security. Yin et al. divided the country into ten basins to conduct an overall study on the change of GWS from 2002-2016 [4]. The results showed that the GWS in most watersheds declined to varying degrees. The average annual decline rate of GWS in the Haihe Basin is -10.30 mm/year, -9.06 mm/year in the Southwest Basin, and -2.45 to -5.54 mm/year in the Liaohe River, Yellow River, Huaihe River, Southeast Basin, and Continental Basin.

Domestic water use, the agricultural sector, industry and municipalities are important groundwater users. Groundwater provides important socioeconomic benefits, but the continued decline in groundwater levels and the resulting depletion of resources has prompted anxiety about the long-term viability of groundwater extraction in Asia.

3.2. Inversion method of GWS based on GRACE

3.2.1. GRACE. In collaboration with the German Space Flight Center, NASA developed the GRACE gravity satellite. A successful launch took place in March 2002, and it ceased operations in October 2017. It provides important support for research on global/regional water storage changes, SLR, and polar/plateau glacier ablation. Following the launch in 2018 of GRACE-FO (GRACE Follow-On), providing continuous observation capabilities for applications in related fields. Basically, terrestrial water storage (TWS) is the whole quantity of water available above and below the ground, among them are groundwater, surface water (lakes and rivers), soil moisture, and snow water. With GRACE observations, monthly TWS changes are quantified with an accuracy of 1–2 cm for equivalent water height and a spatial resolution of 350 km [14]. Water balance equation for (1):

$$\mathrm{TWS} = \mathrm{GW} + \mathrm{SW} + \mathrm{SM} + \mathrm{SWE} \tag{1}$$

Here, the term SW stands for surface water, GW for groundwater, SM for soil moisture, and SWE for snow water equivalent.

3.2.2. Global Hydrological Model. The global hydrological model simulates complex hydrological phenomena in nature based on the water balance formula, and is an important means of studying hydrology [15]. The model usually divides the research a rea into the surface, soil aquifer, and groundwater layer in the vertical direction, and then calculates the hydrological processes in each layer and between layers. The PCR-GLOBWB and WaterGAP models are the most commonly used hydrological model data [4].

The WaterGAP is an analysis and prediction model with a resolution in terms of time and space of 0.5° and daily constructed by the University Kassel Germany[16]. Not only are long-term average water resources calculated for individual countries or basins, but all components of terrestrial water storage, except glaciers, are simulated, including soil water, runoff, groundwater recharge, surface snow cover, and surface water storage changes. WaterGAP is one of the best-known and most successful global-scale hydrological models.

Van Beek of Utrecht University in the Netherlands developed PCR-GLOBWB, a model of global hydrology based on grids [17]. Its spatiotemporal resolution is 0.5° and day. The hydrological cycle between the atmosphere, surface, and subsurface is simulated, including precipitation, surface runoff, soil evaporation, and plant transpiration, while snow accumulation, snowmelt, and glacier melting are also considered. PCR-GLOBWB is also one of the best-known global-scale hydrological models. A summary of the dominant commonly used hydrological models is illustrated in Table 1.

Table 1. Summary of parameters of the most commonly used hydrological models

Model	Resolution	SWE[a]	CWS[b]	SWS[c]	SMS[d]	GWS[e]	Ant. ac.[f]	SL (m)[g]	Soil str. (no.)[h]
WaterGAP	0. 5°，1d	√	√	√	√	√	√	0.1-4.0	1
PCR-GLOBWB	0. 5°，1d	√	√	√	√	√	√	1.5	2

[a] snow water equivalent; [b] canopy's water storage; [c] surface water storage; [d] soil moisture storage; [e] groundwater storage; [f] anthropogenic activity; [g] subsoil level; [h] soil stratification.

3.2.3. Global Land Surface Model. The land surface model is a computer program established for the power and water interaction process among the atmosphere, the ground, and the soil layer. Several land surface process models are commonly used, including Noah, VIC, CLM, and Mosaic. These four models are from the GLDAS, and NASA and NOAA co-developed. Available data include near-surface air temperature, precipitation, SWE, CWS, and SMS. Noah (V3.3) has a lower bias and uncertainty than CLM, VIC, and Mosaic among the GLDAS models. [18]. As shown in Table 2, the most commonly used land surface models have the following properties.

Table 2. Summary of properties of the most commonly used Land Surface Models

Model	Resolution	SWE[a]	CWS[b]	SWS[c]	SMS[d]	GWS[e]	Ant. ac.[f]	SL (m)[g]	Soil str. (no.)[h]
NOAH	0.25°，3h or 1m	√	√	×	√	×	×	3.5	4
MOSAIC	0.25°，3h or 1m	√	√	×	√	×	×	1.9	3
CLM	0.25°，3h or 1m	√	√	√	√	√	×	3.4	10
VIC	0.25°，3h or 1m	√	√	×	√	×	×	3.5	3

3.2.4. GWS inversion research based on GRACE and global hydrological and Land Surface Model. GWSA is the subtraction of SWE Anomaly, SWS Anomaly, SMS Anomaly, and CWS Anomaly from TWSA. The formula is (2):

$$\mathrm{GWSA} = \mathrm{TWSA} - \mathrm{SWSA} - \mathrm{SWEA} - \mathrm{SMSA} - \mathrm{CWSA} \tag{2}$$

Using GRACE satellite products, TWSA is provided. SWE Anomaly, SWS Anomaly, SMS Anomaly, and CWS Anomaly are provided by the Hydrological Land Model. Many studies have shown that groundwater components in total TWS can be successfully separated from GRACE products, for example, estimates of groundwater change from 2002 to 2017 in North America [19], India [20], the Bengal Basin [21], the southern Murray-Darling Basin in Australia [22], Poland [23]. In China, some studies have used GRACE to monitor typical areas of persistent groundwater depletion, for example the national GWS [24][4], Jilin Province [25], North China Plain [26]. Various regions around the world rely heavily on it for studying GWS changes.

3.2.5. Joint inversion of GRACE and other geodetic techniques. As the mass near and at the surface of the Earth redistributes it changes its shape, and these changes over time can be observed with GRACE, GNSS (including GPS), InSAR, and VLBI. As the Earth's surface moves, the location time series records them due to small but measurable loads due to SLR, atmospheric, glaciers and ice sheets, snowfall, rainfall, water storage, and the deformation of the Earth associated with climate change. Despite differences in spatio-temporal resolution, estimates of water load remain a high degree correlated [9][27][28].

By combining GRACE and other geodetic methods, you can reduce variance and improve agreement between TWS and GRACE. GRACE TWS can cover the whole globe but its resolution is low, while GNSS has high spatio-temporal resolution in points. By combining them, GNSS low-density areas are enhanced and TWS estimates are more consistent [27]. Groundwater storage changes were assessed using GRACE and InSAR using the Subsidence Feature Weighted Combination (NSFWC) proposal, resulting in an improvement of GWSA from 0.5°-0.05° in spatial resolution. [28]. By using this procedure, not only can the spatial characteristics of GWS variations be preserved, but also the local complexities relating to subsidence of the surface can be recognized.

3.2.6. Inversion accuracy of GWS based on GRACE. From the perspective of monitoring accuracy, the change of groundwater storage based on GRACE satellite data is basically consistent with the trend reflected by the measured groundwater samples, and the statistical significance of the quantitative comparison between the two are higher than 0.65. Among them, Zhi yong et al. estimates of shallow GWS changes in the North China Plain have the highest correlation with field measured data, with an R^2 of 0.91[29]. In most studies, the correlation coefficient between groundwater storage change results obtained based on GRACE data and field measured data is 0.7-0.8(Table 3).

Table 3. Inversion accuracy of groundwater storage based on GRACE

Study area	Area	Period	Models	Correlation degree	References
North China Plain, China	5.4	2003—2013	GRACE+LSMs	R^2=0.91	[29]
Polish basins (Vistula and Odra)	31.34	2006—2016	GRACE+GLDAS	R^2=0.90	[23]
Alberta, Canada		2002–2014	GRACE+LSMs	R^2=0.68	[30]
West Bengal, India	6,882	2007—2017	GRACE+GLDAS	R^2=0.83	[20]
Yellow River Basin, China	68.0	2005—2014	GRACE+GLDAS/ WaterGAP	R^2=0.72	[31]

3.3. Study on consequences of groundwater depletion based on multi-source Satellite

3.3.1. Land subsidence due to groundwater depletion. Land subsidence is a phenomenon of ground subsidence caused by underground solid or fluid mining, and it is a slow and gradual geological disaster. Although more than 200 areas of subsidence due to excessive groundwater extraction have been reported in 34 countries over the past century, far more areas have actually experienced land subsidence. Only a few countries currently recognize the hazard of land subsidence and take mitigation measures. Scholars used the global land subsidence model, combined with future global water stress, climate and population changes, to predict that the global potential subsidence area will increase by 7% in 2040, affecting 1.6 billion residents, of which 635 million people will live in flood-prone areas [11]. Most funnel-shaped settlements were found along the coast of Zhejiang Province, where the subsidence rate is usually less than 30mm/year. which is considered to be mainly caused by the over-exploitation of groundwater by factories [32].

With the continuous improvement of GNSS, GNSS deformation monitoring technology is becoming more and more mature. In the settlement monitoring of many large-scale projects, the monitoring method based on GNSS technology is adopted. This method uses GNSS precise single-point positioning technology, which can accurately measure the coordinates of the monitoring station and obtain settlement data. It has the characteristics of high monitoring accuracy and less restrictive conditions. Since the overall deformation of the surface can be obtained, it is also widely used in deformation monitoring of dams, landslides, foundation pits, etc.

A growing number of InSAR techniques are used to detect land subsidence and hydrogeological properties. Global coverage, high accuracy, and high resolution are advantages of this method, but its effectiveness in densely vegetated areas is limited. There has been widespread use of the PS-InSAR and SBAS algorithms for urban deformation monitoring. Since persistent scatterers maintain a relatively constant phase and amplitude over time, space-time decoherence, atmospheric delay, and noise are effectively reduced. Land subsidence data at the basin-scale can be obtained through Sentinel-1 imagery, which is becoming more accessible.

3.3.2. Seawater intrusion due to groundwater depletion. Two basic conditions must be met for seawater intrusion to form: hydrodynamic and hydrogeological conditions. When they are met together, seawater intrusion will inevitably occur. Under natural conditions, the groundwater level has a greater value than the sea water level, and the ground fresh water flows in the direction of sea water, and sea water intrusion does not occur. However, when the mining volume exceeds the allowable mining volume, the underground freshwater table will continue to decline, changing the original balance between groundwater and seawater, thus providing the dynamic conditions for the flow of seawater to freshwater, leading to seawater intrusion. In addition, certain hydrogeological conditions must be provided, and there must be a "channel" connecting seawater and fresh groundwater. Many seawater intrusion areas identified by research have this condition.

For seawater intrusion, seawater intrusion can be evaluated by judging the relative difference between groundwater level and seawater level, combined with coastal hydrogeological conditions. The groundwater wells are used to monitor groundwater levels, and then combined with GRACE, satellite altimeter, tide data, etc. to obtain the change of coastal sea level in the study area to obtain the hydrodynamic conditions of seawater intrusion. The possibility of seawater intrusion is comprehensively evaluated in combination with the rock formation properties in the study area.

Monitoring changes in groundwater salinity in aquifer systems to assess seawater intrusion. Sampling groundwater and measuring DC resistivity are common methods for measuring the salinity of aquifer systems [33]. Traditional methods, however, require a long measurement period and a large measurement range, which makes them costly and time-consuming. The potential for seawater intrusion can be assessed by identifying variables that affect groundwater salinity, such as: aquifer transmittance, distance from the ocean, annual rainfall, evaporation rate, elevation, and height of the groundwater level. Various satellite data can quantify these variables into physical variables, combined with GIS or artificial intelligence, to predict salinity levels in groundwater. According to Sahour et al., combining field sampling with this idea is extremely valuable for estimating groundwater salinity [33].

3.3.3. Relative sea level rise due to groundwater depletion. Climate-induced SLR and coastal land subsidence combine to alter relative sea level changes near the world's coasts. The essential cause of land subsidence caused by excessive exploitation of groundwater resources is the compaction of loose unconsolidated soil. The exploitation of groundwater causes the volume of the soil to compress, the pore water pressure in the soil layer decreases, the effective stress on the aquifer increases, and then compression deformation occurs, forming a large area of uneven settlement. In densely populated areas, such as coastal megacities and deltas, this is more likely to occur. Nicholls et al. estimated that delta and urban subsidence accounted for 51-70% of the total global mean relative sea level rise experienced by humans [12]. Tang et al. used the method of combining InSAR, GPS and tide gauge observations to evaluate the Tianjin coastline RSLR. They found that in aquaculture areas along coastlines, land subsidence rates as high as 82 mm/yr due in part to the extraction of groundwater for fisheries contributed to local SLR nearly 30 times faster than on average around the world [34]. The depletion of groundwater caused by overexploitation of groundwater in coastal areas is the main driving factor of land subsidence. Considering the sea level rise caused by climate, the risks of coastal flooding and storm surges have also increased.

Globally speaking, the warming of sea water will cause the sea level to rise. On average, for every 1°C increase, the sea level will rise by 7cm. As the sea water becomes thinner, the density decreases, which will also slightly cause the sea level to rise, and the other is the reason for the melting of glaciers. In the past few decades, groundwater pumping has caused rapid deformation of the ground [28]. As a result of land subsidence and climate-induced SLR, sea level levels around the world have changed relative to one another. There is a four-fold increase in the mean RSLR rate compared to global sea level rise observations [12].

Global SLR impacts on coastal regions have been much considered, but less attention has been given to RSLR from land subsidence [12]. GNSS, InSAR and other surface subsidence technologies combined with GRACE, satellite altimeter, and tide data to obtain regional relative sea level changes. In addition, high spatial variability in land subsidence rates causes RSLR rates to vary from place to place. The free data made available by the Sentinel-1 mission with a large illuminated orbit (250 km) and an extended repetition cycle (6 or 12 days) make it an attractive data source for studying coastal land movement with broad region coverage. GRACE can also try to obtain land subsidence at a large spatial extent [35]. The synthesis of multi-source data provides more reliable decision support for disasters such as floods and storm surges in coastal areas.

4. Conclusion

Based on the literature review of groundwater research worldwide, overexploitation and depletion of groundwater have been identified. The depletion of groundwater, a non-renewable resource, threatens the sustainability of water supply. Authorities should pay more attention to the efficient use and development of groundwater resources, monitor groundwater reserves, and restore depleted areas. Joint groundwater inversion based on GRACE and the Global Hydrological Land Model is summarized, and joints with other geodetic techniques are also discussed. The accuracy of joint inversion based on GRACE is reviewed, and it is shown that the groundwater inversion results based on GRACE have a high correlation with the measured groundwater level. With the launch of a new generation of gravity satellites, it is expected to improve the accuracy of groundwater storage inversion, which requires our further research. Finally, studies addressing a range of adverse consequences of groundwater depletion are discussed. Combined with satellite geodetic technologies such as GRACE, GRACE Follow-On, InSAR, GNSS, and satellite altimeter, exploreable research ideas are proposed for issues and it involves the subsidence of the land, the intrusion of seawater, and RSLR, and further in-depth research is needed in the future.

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