Spatiotemporal coupling analysis of surface water and groundwater in Tibet based on multi-source sensors

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Abstract

Lakes and groundwater are two crucial components of the global terrestrial water cycle, collectively forming a vital network for Earth's water resources. However, in the Tibetan region, the spatiotemporal relationship between lakes and groundwater and their impact on the local hydrological cycle remain inadequately understood. Satellite remote sensing serves as an effective observational tool, enabling comprehensive investigation and analysis of surface lakes and groundwater in Tibet with high spatial resolution. Therefore, this study integrates Landsat and Cryosat-2 satellite data to examine the spatiotemporal patterns of surface lake extents and water levels in Tibet. Additionally, combining Gravity Recovery and Climate Experiment (GRACE) satellite observations with the Global Land Data Assimilation System (GLDAS) model data, we quantitatively analyze the spatiotemporal variations in groundwater storage and its correlation with lake water. The results indicate that: 1)Rivers and lakes in Tibet are mainly located in the central and northwest regions, displaying noticeable intra-annual variations; 2) Substantial lagged relationships exist between groundwater storage and lake water levels and areas, revealing that lakes contribute significantly to groundwater replenishment, especially in the Ngari prefecture and Lhokha prefecture. This study comprehensively utilizes multi-source remote sensing data to dynamically monitor surface and groundwater in Tibet, providing robust support for a better understanding of the interaction between groundwater and surface water.

1. Introduction

Rivers and lakes are important components of the global water cycle, providing vital ecosystem services to human society.(Vörösmarty, 2010)。Surface rivers and lakes undergo seasonal and weather-scale expansion and contraction, influenced by specific climatic conditions such as heavy rain or drought.(Jensen, 2017)These fluctuations have implications for the surrounding environment, impacting ecosystem services. (Yang, 2019) 。 Therefore, understanding the response mechanisms of rivers to surrounding environmental factors is crucial for addressing global climate change and promoting the healthy development of ecosystems. Groundwater, as part of the water cycle, is interconnected with surface rivers, lakes, and other hydrological elements.(Winter, 1999) 。 This interconnected relationship is often bidirectional, meaning that rivers replenish groundwater during the rainy season, while groundwater plays a crucial role in maintaining the basic ecosystem services of rivers during the dry season.(Mukherjee, 2018)。However, over the past few decades, human activities have altered the balance between rivers, lakes, and groundwater, posing serious threats to regional water resource management and ecosystem preservation. Therefore, quantifying the interactions between rivers, lakes, and groundwater is of significant importance for maintaining water resource balance and promoting ecological conservation.

Traditional methods rely on field measurements and laboratory analyses to analyze and simulate the exchange of quantity and quality between surface water and groundwater(Gudmundsson, 2019; Parlov, 2019; Kazakis, 2016). However, data collection using these methods requires significant human and material resources and is not suitable for large-scale regional simulation studies. Therefore, some numerical simulation methods are widely applied to simulate large-scale interactions between surface water and groundwater. For example, the SWAT and MODFLOW models can simulate groundwater flow and surface water-groundwater interactions(Bailey, 2020) However, these models require stringent data inputs, posing significant challenges to simulation accuracy. Remote sensing data provide a foundation for rapidly acquiring large-scale research on rivers and groundwater. Since 1984, Landsat has continuously collected multispectral information of the Earth's surface at a spatial resolution of 30 meters(Wulder, 2016), supporting the retrieval of surface water data(Yang, 2020; Pekel, 2016)。Furthermore, the Gravity Recovery and Climate Experiment (GRACE) dataset, along with GRACE assimilation into land surface models, enables analysis of the spatiotemporal trends in global surface and groundwater storage(Soltani, 2021; Tariq, 2023)，, thereby providing data support for studying relationships between river discharge and other terrestrial water storage components(Gao, 2021)。

As the source of three major rivers, the Tibetan region plays a crucial role in providing significant ecological services. Due to its unique geographical location, Tibet is considered one of the most sensitive areas to climate change (Chen and Yao, 2021). Under the influence of global climate change and human activities, Tibet is facing significant threats of depletion in both surface water and groundwater resources. Therefore, studying the interaction mechanisms between surface water and groundwater in Tibet is of paramount importance for water resource management and ecological preservation. This study will utilize multi-sensor satellite data to analyze the spatiotemporal evolution patterns and interaction relationships between surface water and groundwater in Tibet, aiming to provide scientific support for regional water resource management.

2. Data and Methods

2.1 Study area

The Tibetan region, situated on the Qinghai-Tibet Plateau, boasts the world's highest average elevation, exceeding 4,000 meters. Its annual average temperature ranges from -5.3° C to 4.1° C, with annual precipitation varying between 262.2 to 772.8 millimeters (Figure 1). Endowed with extensive glaciers and unique terrain, Tibet possesses abundant water resources. Notably, it serves as the source of major rivers in China such as the Yangtze and Yellow Rivers, as well as numerous rivers flowing through Southeast Asia, South Asia, and even Central Asia. Moreover, Tibet is home to a concentration of the world's largest inland lakes. Studies indicate the presence of around 1000 lakes with an area exceeding 1km^2, totaling approximately 800km^2 in lake area.(Lei, 2013). Since the 1950s, with the exacerbation of global climate change, the Tibetan region has experienced a significant rise in temperatures, leading to changes in its surface water area.

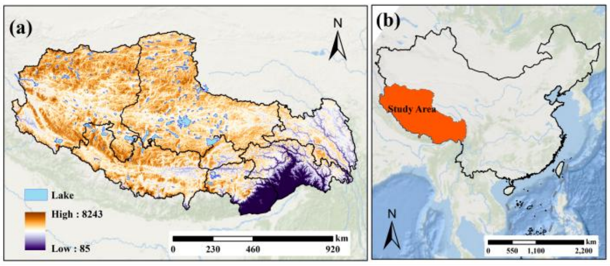

Figure1. Overview map of the study area

2.2 Data

2.2.1 Landsat

This study selected a total of 128 satellite images for each month from 2010 to 2020 to identify surface water bodies within the study area and calculate the total water area. Each image was acquired at a spatial resolution of 30 meters. The images used in the study were obtained and processed using the Google Earth Engine (GEE) platform, which provides functionalities such as geometric correction, atmospheric correction, and cloud removal algorithms (Foga, 2017) to ensure the accuracy and reliability of the image data. To accurately delineate the spatial extent of surface water bodies, this study utilized the Normalized Difference Water Index (NDWI) to extract water features.

2.2.2 Cryosat-2/SIRAL data

Cryosat-2/SIRAL altimetry data are based on three modes, enabling global surface height measurements, including:

1) Low-Resolution Mode (LRM): Primarily used for observing surface values in relatively flat terrains, both over land and ocean areas.

2) Synthetic Aperture Radar (SAR) Mode: Mainly employed for measuring the height of land ice sheets and sea ice.

3) Synthetic Aperture Radar Interferometric (SARIn) Mode: Primarily utilized for measuring the height of high mountain glaciers and ice sheet margins with complex and steep terrain.

This study utilized CryoSat-2/SIRAL GDR (Geophysical Data Record) data from July 2010 to July 2020, which are released by ESA (European Space Agency) and are available for free download at ftp://scientist-pds.cryosat.esa.int. The GDR data are composite products derived from three measurement modes processed sequentially over time.(Xu, 2020)。In addition to height measurements, GDR data also include geographic location, orbital position, and measurement time information, fulfilling the research requirements of most scientists.

2.2.3 Land Total Water Storage

Land Total Water Storage (TWS) anomalies can be derived from GRACE data products (Long, 2017). Currently, this product has advanced to its sixth generation and is available from different suppliers, including CSR (Center for Space Research), GFZ (GeoForschungs Zentrum), and JPL (Jet Propulsion Laboratory) versions. This study utilized the fifth-generation Mascons product provided by CSR (Save, 2016), which minimizes common errors and harmonic noise in GRACE satellite data calculations. The spatial resolution of this product is 0.5°, and it does not require post-processing for use. TWS data from July 2010 to July 2020 were selected for calculating changes in groundwater storage in the Qinghai-Tibet Plateau.

2.2.4 GLDAS data

GLDAS (Global Land Data Assimilation System) is a set of land surface models that represent surface states and fluxes by coupling satellite observation data, surface observation data, and model output reanalysis parameters(Rodell, 2004)GLDAS (Global Land Data Assimilation System) is a set of land surface models that represent surface states and fluxes by coupling satellite observation data, surface observation data, and model output reanalysis parameters(Hiroko, 2016).

2.3 Method

2.3.1 Estimation of Groundwater Storage

The Total Water Storage (TWS) derived from GRACE data consists of two components: the terrestrial water component containing surface water, soil moisture, and snow water, and the groundwater component, as illustrated in Equation 1.

$$\Delta TWS = \Delta W_{can} + \Delta W_{soi} + \Delta W_{sno} + \Delta GWS \quad (1)$$

Where ΔW_{can}, ΔW_{soi} and ΔW_{sno} represent the changes in storage of canopy water, soil water, and snow water, respectively. Therefore, Δ GWS can be calculated using Equation 2:

$$\Delta GWS_{GRACE} = \Delta TWS - (\Delta W_{can} + \Delta W_{soi} + \Delta W_{sno}) \quad (2)$$

However, using GRACE alone cannot separate the different components of TWS. Therefore, it is necessary to utilize additional auxiliary data to separate groundwater storage components. In this study, GLDAS data are used as auxiliary data for estimating groundwater storage. However, since these two datasets have different resolutions, interpolation processing

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of the GRACE data is required before subtracting the surface water storage component to ensure consistency in spatial resolution between the two datasets and thus maintain the validity of the data calculation.

2.3.2 Time Lagged Cross-Correlation

Previous studies have indicated that rivers and lakes, as dynamic components of surface water storage, exhibit certain lagged relationships with groundwater at different temporal and spatial scales (Gao, 2021). This suggests that changes in river and lake water levels may lag behind changes in groundwater levels under the mutual replenishment relationship between groundwater and surface water. Therefore, this study employs the Time Lagged Cross-Correlation (TLCC) method (Tang, 2010)to quantify the spatiotemporal correlation characteristics between river and lake water and groundwater in the Tibetan region. TLCC is widely used to analyze the interaction between two time series. It can analyze the lead/lag relationship between two time series, as shown in Equation (3).

$$TLCC(X_t,Y_t)=\frac{\sum_{t=0}^{N-1-K}(x_{t+1}-\overline{x_t})(y_{t+1}-\overline{y_t})}{\sqrt{(x_{t+1}-\overline{x_t})^2(y_{t+1}-\overline{y_t})^2}} \quad (3)$$

In the equation, x_t and $y_t$are the observed values in the two time serie X_t and Y_t; $\overline{x_t}$ and $\overline{y_t}$denote the means of X_t and Y_t; trepresents the day of the year (DOY); k represents the time lag between the two time series x_t and y_t; nrepresents the number of days in a year. The TLCC value ranges from -1 to 1, where a larger absolute value indicates a stronger correlation between the two time series.

3. Results and analysis

3.1 Analysis of Spatiotemporal Trends in Water Resources in Tibet

Figure 2 depicts the spatiotemporal trends in the extent and water level of surface lakes in Tibet. The results indicate pronounced seasonal and interannual variations in the area and water level of rivers and lakes in Tibet. Interannually, there is an overall increasing trend in the area and water level of rivers and lakes in Tibet, suggesting a continuous increase in surface water storage in the region. Specifically, there are prominent peaks in both area and water level in 2014 and 2016. Seasonally, the months of June to August exhibit the maximum area and water level of rivers and lakes in Tibet. During this period, as rainfall and snowmelt increase, Tibet experiences a peak in surface water, which is beneficial for local ecosystem development and groundwater replenishment.

To further analyze the spatial trends in surface water resources in Tibet, this study employs "water occurrence frequency" to reflect the seasonal variability of surface water. The results indicate that over 50% of rivers and lakes in Tibetan lake regions exhibit a water occurrence frequency between 80% and 100%, suggesting a certain level of stability in most water bodies. Moreover, these long-term persistent rivers and lakes are mainly distributed in the major southern Tibetan regions, which not only have large areas of rivers and lakes but also exhibit high stability in these water bodies. In contrast, the northern Tibetan regions have relatively smaller areas of rivers and lakes, with most rivers and lakes exhibiting a water occurrence frequency of only 0-20%, indicating stronger seasonal and interannual variability in water volume in this area.

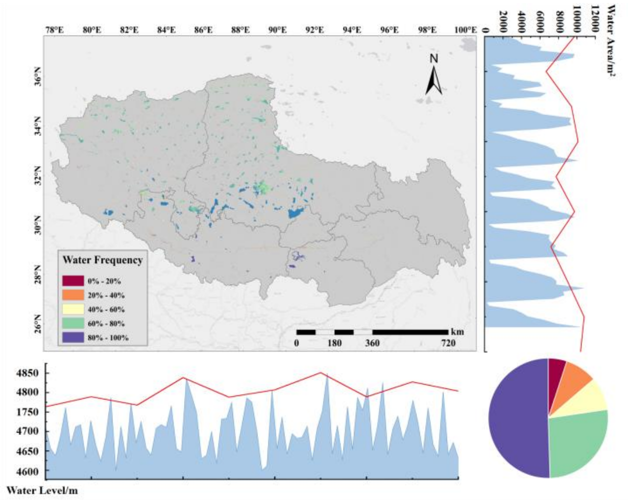

Figure2. spatial and temporal variation of lake area and water level in Tibet

Furthermore, this study further analyzed the spatiotemporal trends in groundwater storage in Tibet from 2010 to 2020, as shown in Figure 3. The analysis reveals that groundwater storage in Tibet exhibits a certain upward trend, although the rate of increase is relatively low. It is worth noting that groundwater storage in different regions of Tibet exhibits strong seasonal fluctuations. Specifically, the Nagqu and Shigatse regions exhibit significant interannual fluctuations, while the Shannan region exhibits notable intra-annual fluctuations. The variation in groundwater storage in Tibet is influenced by multiple factors, including climate change and human activities. During the summer, increased snowmelt and precipitation will further replenish both surface water and groundwater, thus contributing to an increase in groundwater storage. In contrast, during the winter, reduced precipitation coupled with increased groundwater extraction can lead to a significant decrease in groundwater storage, resulting in pronounced seasonal fluctuations in groundwater storage. Additionally, exacerbated by climate change and urbanization, overexploitation of groundwater in Tibet worsens, leading to more complex changes in regional groundwater storage. Strong interannual and intra-annual fluctuations are likely to have a profound impact on regional ecosystems.

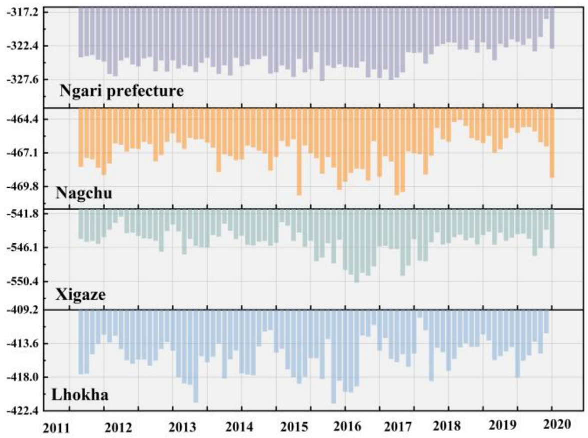

Figure3. Spatiotemporal variation law of groundwater reserves in Tibet

3.2 Analysis of the Relationship between Surface Water and Groundwater in Tibe

Due to the inherent lead-lag relationships between surface water and groundwater recharge, this study employs a time-lagged cross-correlation analysis method to elucidate the relationship between surface water and groundwater in Tibet. The results are depicted in Figure 4, which respectively present the lagged analysis of surface water area and water level with groundwater storage in the Ali, Shannan, Nagqu, and Shigatse regions.

The correlation coefficients between groundwater storage and surface water area in the Ali, Shannan, Nagqu, and Shigatse regions are 0.33, -0.15, 0.14, and -0.04, respectively. Meanwhile, the correlation coefficients between groundwater storage and surface water level are 0.21, 0.23, 0.23, and 0.22, respectively. Overall, there is a certain degree of mutual replenishment relationship between surface water and groundwater in Tibet. That is, the increase or decrease in surface water directly impacts changes in groundwater storage, with this impact exhibiting certain lead-lag characteristics.

In the Ali region, groundwater storage changes show a positive correlation with surface water, with groundwater changes leading surface water area and water level by 6 and 1 time steps, respectively. This suggests that groundwater mostly replenishes surface water, and the changes in water level are more closely related to changes in groundwater storage. The correlation results in Nagqu are consistent with those in Ali. However, in Shannan and Shigatse, surface water and groundwater exhibit a negative correlation, with groundwater changes lagging behind area changes by 10 and 5 time steps, respectively. In Shannan and Shigatse, surface water plays a dominant role in replenishing groundwater, and this phenomenon may be closely related to human activities.

In conclusion, the interaction between surface water and groundwater in Tibet exhibits complex spatial characteristics, reflecting the diversity of water supply and replenishment relationships between surface water and groundwater in different regions. This diversity is closely associated with human activities.

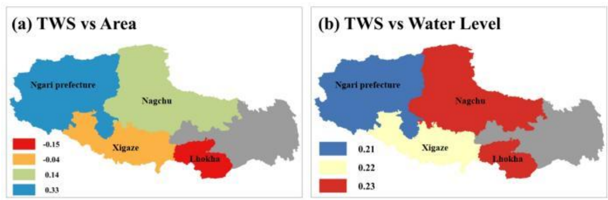

Figure4. Results of hysteresis analysis of groundwater and surface water

4. Conclusion

Based on the analysis of multiple sensor data sources, this study has drawn the following conclusions regarding the spatiotemporal coupling relationship between groundwater and surface water in Tibet:

1) Surface water resources in Tibet exhibit significant seasonal and interannual variations, showing an overall increasing trend, particularly reaching prominent peaks in 2014 and 2016. The summer months (June-August) witness the highest surface water area and water level, which is attributed to increased rainfall and snowmelt, contributing positively to the ecosystem and groundwater replenishment.

2) Groundwater storage in Tibet shows a certain upward trend from 2010 to 2020, albeit with a relatively low rate of increase. Changes in groundwater storage are influenced by climate change and human activities, with increased snowmelt and precipitation in summer favoring groundwater storage

increase, while reduced precipitation and overexploitation of groundwater in winter lead to a decrease in groundwater storage.

3) In Tibet, there exists a certain mutual replenishment relationship between groundwater and surface water, but the impact exhibits certain lead-lag characteristics. In the Ali and Nagqu regions, groundwater predominantly replenishes surface water, while in the Shannan and Shigatse regions, the opposite is observed, with surface water primarily replenishing groundwater. The complex relationship between surface water and groundwater is influenced by regional characteristics and human activities.

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