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GNSS DATA MONITORING DROUGHT: CURRENT APPLICATIONS AND OUTLOOK

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Abstract— Continuous and dense observations from the Global Navigation Satellite System (GNSS) have emerged as a pivotal tool for drought monitoring. Currently, the most prevalent approaches for drought monitoring using GNSS data fall into two categories: hydrological drought monitoring, which relies on the inversion of terrestrial water storage (TWS) variations, and meteorological drought monitoring, derived from atmospheric precipitable water vapour (PWV). While GNSS has become a focal point of research in hydrogeology, comprehensive studies systematically exploring the use of GNSS data in extreme drought monitoring still need to be expanded. Few studies have provided a comprehensive and systematic overview of meteorological and hydrological drought monitoring based on GNSS data. This study utilizes bibliometrics to analyze GNSS-based extreme drought monitoring research, explores its principles and methods, and discusses current limitations and future directions, aiming to guide future research on regional drought changes and applications using GNSS technology.

I. Introduction

Drought, a widely recognized natural disaster, has the most extensive impact and causes the significant agricultural losses. It also severely affects the ecological environment and socioeconomic conditions [1]. Under the combined influence of climate change and human activities drought exhibits an increasing frequency of occurrence and escalating losses. A standard definition of drought categorizes it into four primary types: meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought [2].

The GNSS represents a pioneering environmental remote sensing method, and offering geodetic-based strategies for drought monitoring [3]. While GNSS has become a focal point of research in hydrogeology, comprehensive studies systematically exploring the use of GNSS data in extreme drought monitoring still need to be expanded. Few studies have provided a comprehensive and systematic overview of meteorological and hydrological drought monitoring based on GNSS data.

This study first employs bibliometric analysis to examine recent trends and characteristics of research on extreme drought monitoring using GNSS. Second, it delves into the fundamental principles and methods of hydrological and meteorological drought monitoring based on GNSS data. Finally, it summarizes and discusses the current limitations and future development trends of GNSS drought monitoring.

II. Methodology

A manual query was conducted in the Web of Science, focusing on SCI (Science Citation Index) and SSCI (Social Science Citation Index). The search term 'TS=("GNSS" OR "Global Navigation Satellite System" OR "GPS") AND TS=("Drought")' was applied to retrieve GNSS-based drought studies. The study identified 241 relevant articles on drought monitoring using GNSS data (search date: June 1, 2024). After reviewing abstracts, 72 highly relevant articles, excluding review papers, were selected for further analysis (Figure 1a). Figure 1b shows the increasing trend of publications on this topic over the years, with prominent journals including Remote Sensing, Geophysical Research Letters, Science of the Total Environment, and Journal of Hydrology.

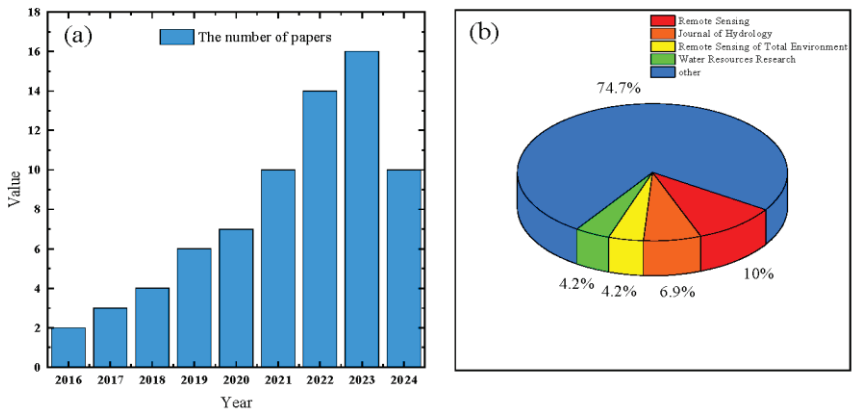

Figure 1: Number of papers and the proportion of published journals on monitoring drought changes using GNSS

III. GNSS Drought Monitoring Indices

A. Drought Index Based on GNSS derived TWS

Recent progress in geodetic technologies has greatly advanced the monitoring of TWS changes caused by the global water cycle [4], establishing hydrological geodesy as a specialized discipline. Among these methods, The Gravity Recovery and Climate Experiment (GRACE) is one of the most commonly used tools for large-scale TWS observation [5]. However, its spatial resolution constraints make it difficult to detect TWS fluctuations at distances below approximately 300 km [6].

On the other hand, GNSS stations, by recording crustal deformation resulting from elastic responses to hydrological loading, offer an independent means of monitoring TWS [7-8]. Their heightened sensitivity to regional hydrological shifts [9] positions GNSS as an essential complement and alternative to GRACE in smaller-scale applications [10].

In 2014, Thomas et al. demonstrated that anomalies in the changes of the TWS, both deficits and surpluses, can serve as indicators for quantifying extreme drought and flood events. In their study, water storage deficit (WSD) is defined as the disparity between changes in monthly water storage and the climatological average for the same month.

$$\boldsymbol{WSD_{i,j} = TWSA_{i,j} - \overline{TWSA_j}} \quad (1)$$

where:

$WSD_{i,j}$ = Difference between the TWSA time series and the monthly mean of TWSA values

$TWSA_{i,j}$ = TWSA time series for the j-th month in i-th year

$\overline{TWSA_j}$ = The long-term mean of TWSA for the same j-th month

Based on the method described above, the high spatiotemporal resolution the TWS changes inverted from GNSS observations can be utilized for studying localized short-term extreme climate events. Currently, GNSS inverted TWS has been applied to the study of extreme drought events in regions such as California, Brazil, Southwest China, and the Tibetan Plateau, demonstrating remarkable capabilities in hydrological drought monitoring [11-13].

Using the northeastern Tibet Plateau from 2011 to 2022 as an example, Figure 2 compares the drought indices GNSS-DSI obtained from GNSS, GRACE-DSI obtained from GRACE, and the self-calibrating Palmer Drought Severity Index (scPDSI). The correlation results indicate a value of 0.63 for GNSS-DSI and GRACE-DSI, and 0.43 for GNSS-DSI and scPDSI, indicating similar temporal characteristics among the three datasets and the results point to GNSS being a valuable resource for observing and evaluating hydrological drought patterns.

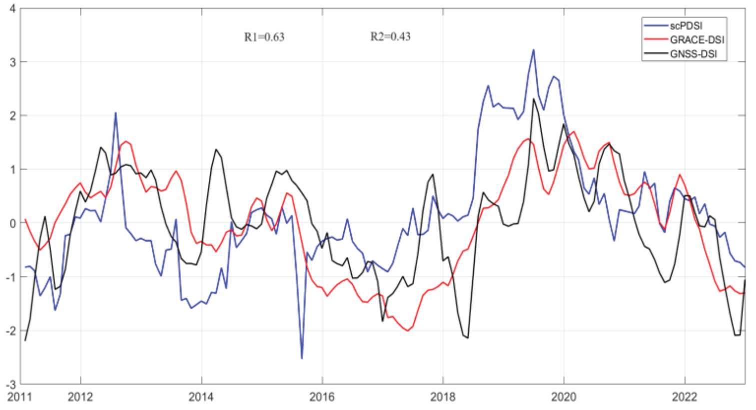

Figure 2: Patterns of drought indices observed in the investigated area [14]

IV. Drought index based on GNSS-derived PWV

As signals traverse the atmosphere, they are subject to delays caused by atmospheric refraction and bending within the troposphere. Advanced parameter estimation methods in GNSS data processing allow the calculation of these delays and, when integrated with ground-based meteorological data, facilitate the determination of atmospheric PWV [15].

In the realm of drought monitoring, the primary applications of GNSS-derived PWV encompass two aspects: enhancing existing drought monitoring indices and developing new drought indices.

In the context of improving drought monitoring indices, research demonstrate that by incorporating GNSS-derived PWV, temperature, and pressure data, the commonly utilized Thornthwaite model can significantly enhance the calculation of Potential Evapotranspiration (PET), thereby improving the drought monitoring capabilities of the Standardized Precipitation Evapotranspiration Index (SPEI) [16-18] .

Drought indices based on PWV rely on examining how atmospheric water vapor transitions into precipitation, offering insights into precipitation efficiency (PE) and its influence on precipitation processes [19].

More precisely, PE, as described in Equation (2) [20], is measured as the ratio of water vapor above a site to the precipitation deposited on the Earth's surface :

$$\boldsymbol{PE = \frac{P}{PWV} \times 100} \tag{2}$$

where:
PE = Precipitation efficiency
P = Monthly average precipitation
PWV = Precipitable Water Vapor

Building on the aforementioned approach, GNSS-derived PWV has been widely employed by researchers for drought assessment, benefiting from its superior resolution in time and space, long-term data series, and accurate insights into atmospheric water vapor variations [21-22].

Considering the limitation of the traditional drought index. In 2020, Zhao et al introduced the Standardized Precipitation Conversion Index (SPCI) for improvement, enabling the identification of multi-scale meteorological droughts.

Currently, the SPCI has demonstrated excellent drought monitoring capabilities in Yunnan and Guangdong provinces of China, as well as in the southern region of Spain [23-24].

Figure 4 uses Guangdong Province as an example to compare the SPCI-derived meteorological drought index with the widely adopted SPI and SPEI indices [25]. Analysis revealed strong correlations between SPCI and these indices across multiple timescales. Moreover, drought event severity grew as the temporal scale lengthened across all indices, underscoring SPCI's capacity to effectively monitor extreme drought conditions in Guangdong.

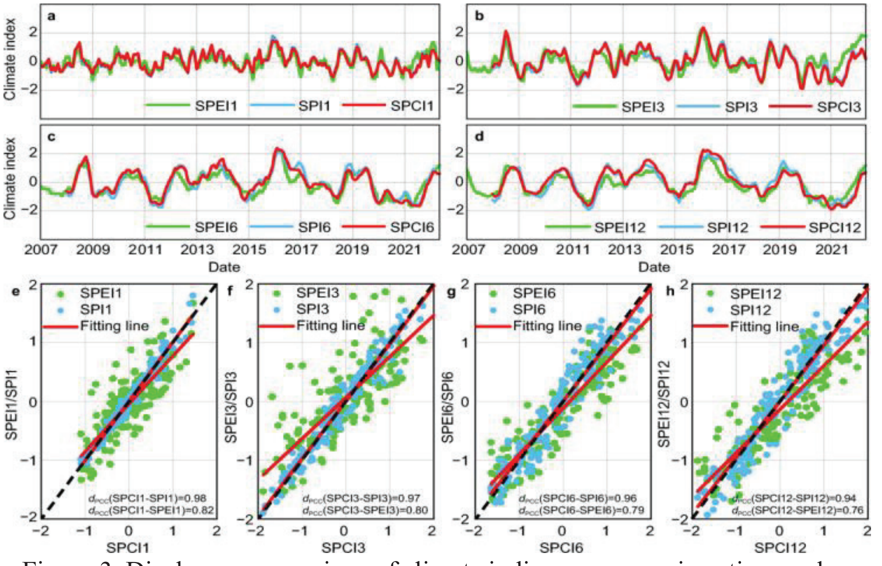

Figure 3: Displays a comparison of climate indices across various time scales, focusing on SPCI, SPI, and SPEI

V. Conclusion

With GNSS technology advancing steadily, its use in drought monitoring has become increasingly recognized. A significant rise in publications is evident, with many studies published in leading journals, including Remote Sensing, Geophysical Research Letters, Science of the Total Environment, and Journal of Hydrology.

This article presents the principles and methodologies of drought monitoring utilizing GNSS, reviews its application advancements in hydrological and atmospheric drought monitoring, and summarizes the shortcomings of existing GNSS techniques in drought assessment. Despite the notable correlation between GNSS-based and conventional drought indices, their application in monitoring accuracy and reliability must address challenges related to site density and extraneous non-hydrological factors.

Therefore, future research should concentrate on integrating GNSS technology with other remote sensing tools to expand the coverage of GNSS stations, thereby further augmenting drought monitoring capabilities. Additionally, as interdisciplinary connections become increasingly robust, the drought monitoring potential exhibited by GNSS will furnish vital references for meteorological and hydrological agencies in devising effective drought mitigation strategies. Specifically, GNSS-based drought monitoring capabilities can provide early warnings and decision support for agricultural production, ecosystem management, and socioeconomic development directly impacted by drought.

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