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A Deficit-Based Groundwater Drought Index (GWDI): Concept, Methodology, and Application in Hard-Rock Aquifers

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Abstract:
Effective assessment of groundwater drought requires indicators that reflect subsurface water stress rather than relying solely on surface hydro-meteorological signals. The Groundwater Drought Index (GWDI), endorsed within India's national drought assessment framework, quantifies groundwater drought by measuring deviations of observed groundwater levels from long-term reference conditions. This study provides a detailed methodological appraisal of GWDI, encompassing its conceptual foundation, mathematical formulation, drought severity categorization, and linkage with non-parametric trend detection techniques. Post-monsoon groundwater level records from a semi-arid basaltic aquifer system are used to demonstrate the applicability and reliability of the index. The analysis shows that GWDI successfully identifies persistent groundwater stress, including periods characterized by above-average rainfall. The findings highlight GWDI as an operationally robust, scientifically credible, and policy-oriented tool for groundwater drought monitoring and sustainable management of hard-rock aquifer systems.

Keywords: *Groundwater drought index; GWDI; groundwater deficit; hard-rock aquifer; post-monsoon groundwater levels*

INTRODUCTION

Groundwater drought represents a slowly evolving hydrological phenomenon marked by delayed manifestation, prolonged duration, and strong control by aquifer characteristics and human-induced groundwater withdrawal. Unlike surface water droughts, its impacts often remain unnoticed until groundwater levels decline significantly, making monitoring and management particularly challenging (Mishra and Singh 2010). In semi-arid hard-rock regions, including the basaltic terrains of peninsular India, groundwater systems are characterized by limited storage, fracture-dominated permeability, and spatially uneven recharge mechanisms (Todd and Mays 2005; CGWB 2017). These hydrogeological constraints frequently result in sustained groundwater stress, even during years that receive normal or above-average rainfall.

Most commonly used drought indices rely on precipitation or soil moisture conditions and are therefore insufficient to capture subsurface water scarcity. This limitation is especially pronounced in hard-rock aquifers, where recharge occurs intermittently and varies significantly across space and time (Custodio and Llamas 2003). Consequently, increasing emphasis has been placed on groundwater-specific drought indicators that directly reflect aquifer conditions rather than surface climatic anomalies (Rodell et al. 2009; El Bouazzaoui et al. 2024). Within this context, the Groundwater Drought Index (GWDI), introduced in India's Drought Management Manual, offers a deficit-oriented approach to groundwater drought assessment by relating observed groundwater levels to long-term reference conditions (Government of India 2016). Although GWDI is operationally adopted in drought monitoring frameworks, its conceptual and methodological foundations have not been adequately explored in peer-reviewed literature. The present study addresses this gap by elaborating the conceptual rationale and mathematical formulation of GWDI and by demonstrating its integration with non-parametric trend analysis for evaluating groundwater drought in hard-rock aquifer systems.

CONCEPTUAL BASIS OF GWDI

The conceptual framework of the Groundwater Drought Index is based on the premise that groundwater drought should be evaluated in terms of departures from long-term aquifer equilibrium rather than through absolute groundwater levels or standardized climatic indices (Mishra and Singh 2010). This distinction is particularly important in hard-rock aquifers, where groundwater systems exhibit slow and dampened responses to rainfall due to low primary porosity and recharge pathways governed by weathering profiles and fracture networks (CGWB 2017). GWDI quantifies groundwater stress by assessing the deviation of observed groundwater levels from long-term mean and extreme conditions for a defined temporal window. By adopting this deficit-based perspective, the index provides a physically meaningful representation of groundwater drought that directly reflects the degree of subsurface water stress experienced by the aquifer system (Government of India 2016). The conceptual framework of GWDI, illustrated in Figure 1, emphasizes its ability to capture groundwater deficits and its compatibility with trend-based statistical analyses, thereby enabling both condition assessment and long-term drought evolution studies.

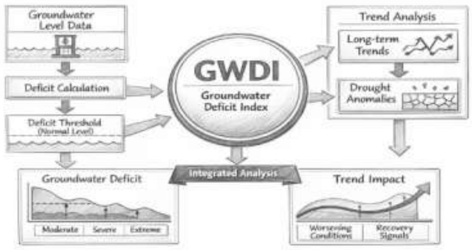

Figure 1: Conceptual Framework for GWDI and Trend-Based Drought Assessment

MATHEMATICAL FORMULATION OF GWDI

The Groundwater Drought Index is computed using the following expression (Government of India 2016):

$$GWDI_{ij} = \frac{MGWD_j - GWD_{ij}}{GWD_{imax}}$$

Where

$GWDI_{ij}$ = Groundwater Drought Index for ith month and jth year

$MGWD_j$=Mean depth to groundwater table below surface (in meter

GWD_{ij}=Depth to groundwater table in ith month and jth year (in meter).

GWD_{imax}=Maximum depth to groundwater table in ith month in available data set for n number of years (in meter).

i = 1,2,3,…,12 (months)

j = 1,2,3,…,n (years)

n= total numbers of years for which monthly groundwater records are used.

In this formulation, negative GWDI values indicate groundwater deficit, with increasingly negative values representing progressively severe groundwater drought conditions. The formulation is distribution-free and does not require transformation or standardization, making it particularly suitable for groundwater time series that often violate normality assumptions (Tabari et al. 2011).

GWDI-BASED DROUGHT SEVERITY CLASSIFICATION

Groundwater Drought Index values are classified into distinct drought severity categories using thresholds recommended at the national level (Government of India 2016). These categories span a continuum from normal groundwater conditions to severe and extreme groundwater drought. Such categorization enhances the interpretability of GWDI outputs, enabling direct use by groundwater managers and policy authorities for drought monitoring, early warning, and mitigation planning.

In contrast to standardized drought indices, the severity classes of GWDI are explicitly linked to deviations in groundwater depth, thereby providing a physically meaningful interpretation of drought conditions. This feature is particularly important in hard-rock aquifer systems, where even minor groundwater level declines can result in substantial socio-economic consequences due to limited storage and high dependence on groundwater resources (Custodio and Llamas 2003).

INTEGRATION OF GWDI WITH TREND ANALYSIS

Although GWDI effectively represents groundwater drought conditions at individual time steps, understanding the progression and persistence of drought requires examination of long-term temporal trends. Groundwater level datasets often exhibit non-normal distributions, missing observations, and outliers, making non-parametric statistical techniques especially suitable for trend detection (Mann 1945; Kendall 1975).

In the present study, GWDI time series are analyzed using the Mann–Kendall test to identify monotonic trends in groundwater drought severity, while Sen's slope estimator is applied to quantify the rate of change over time (Sen 1968). The combined application of GWDI with these trend analysis tools enables differentiation between short-duration groundwater stress associated with climatic variability and long-term groundwater depletion primarily driven by anthropogenic extraction pressures (Rodell et al. 2009; Abhishek and Kinouchi 2022).

APPLICATION IN HARD-ROCK AQUIFERS

The application of GWDI to post-monsoon groundwater level observations from a semi-arid basaltic aquifer system highlights the capability of the index to capture sustained groundwater stress. The results indicate that groundwater deficits persist even during years receiving above-average rainfall, underscoring the influence of limited recharge efficiency and increasing groundwater abstraction in hard-rock terrains (CGWB 2017; GSDA 2023).

Trend analysis of the GWDI time series reveals a consistent and gradual intensification of groundwater drought conditions, as reflected by positive Sen's slope values. These patterns align with previous studies documenting the weakening relationship between rainfall variability and groundwater recovery in hard-rock regions of India, where anthropogenic pressures increasingly dominate groundwater dynamics (Rodell et al. 2009; Abhishek and Kinouchi 2022).

ADVANTAGES OF GWDI

In comparison with conventional drought indicators, the Groundwater Drought Index offers several distinct advantages:

- Direct quantification of groundwater deficit
- Suitability for hard-rock aquifer environments
- Distribution-free formulation that avoids statistical assumptions
- Consistency with nationally adopted drought assessment frameworks

  These attributes make GWDI a dependable and operationally efficient tool for groundwater drought evaluation and long-term groundwater resource planning.

CONCLUSIONS

The Groundwater Drought Index provides a scientifically sound and operationally straightforward approach for assessing groundwater drought in semi-arid hard-rock aquifer systems. By adopting a deficit-based formulation, GWDI directly represents subsurface water stress without relying on assumptions inherent to standardized climatic indices. When combined with non-parametric trend analysis methods, the index facilitates assessment of both the severity and temporal evolution of groundwater drought, enabling distinction between transient hydrological stress and persistent groundwater depletion. The framework presented in this study supports broader adoption of GWDI in groundwater drought research and strengthens its applicability for operational drought monitoring and sustainable groundwater management.

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