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HYDROLOGICAL DROUGHT ASSESSMENT USING GEOSPATIAL TECHNOLOGY OF THE YERLA RIVER BASIN, MAHARASHTRA (INDIA)

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Abstract

Hydrological drought poses significant challenges to surface and groundwater resources, impacting agriculture, ecosystems, and water management strategies. This study examines hydrological drought in the Yerla River Basin, Maharashtra, using the Groundwater Drought Index (GWDI) and Standardized Groundwater Index (SGI). Groundwater level data from 32 observation wells (1994–2023) were analyzed to assess temporal drought trends and delineate spatial drought risk zones through Geographic Information System (GIS) techniques. The GWDI quantified groundwater drought by evaluating water table deviations, while the SGI standardized fluctuations for effective monitoring. The findings highlight severe drought periods, notably 2000–2003 and 2011, with significant regional variations in intensity. Post-monsoon GWDI assessments identified acute drought conditions in Kadegaon and Khambale Aundh, while pre-monsoon analysis revealed prolonged drought persistence in Hanmantvadiye and Kadegaon until 2003, followed by partial recovery. SGI results reinforced these trends, pinpointing severe drought hotspots in Kadegaon, Khanapur (Sangli), and Khatav (Satara). Spatial interpolation using Inverse Distance Weighting (IDW) and weighted overlay analysis classified drought severity into five levels, aiding in vulnerability mapping. The study underscores the need for proactive drought mitigation strategies, including early warning systems, enhanced groundwater monitoring, and community-driven water conservation measures. By integrating GIS-based techniques with groundwater data, this research provides critical insights into drought dynamics and supports the formulation of adaptive water management policies tailored to semi-arid regions like the Yerla River Basin.

Keywords: Hydrological Drought, GWDI, SGI, Geospatial Technology.

Introduction

Hydrological drought, characterized by a significant reduction in surface and groundwater resources, is a critical issue exacerbated by prolonged periods of below-average precipitation. It manifests through reduced streamflow, declining groundwater levels, and diminished reservoir storage, posing severe challenges to water resource management, agricultural productivity, and ecosystem health. As climate variability intensifies, understanding the dynamics of hydrological drought and its impacts has become increasingly important for developing adaptive strategies to mitigate water scarcity and ensure sustainable resource management.

To analyse hydrological drought, this study employs two key indicators: the GWDI and the SGI. The GWDI, as outlined in the Drought Manual 2016, is specifically designed to evaluate groundwater levels for agricultural and drinking water purposes. However, its

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application requires extensive and continuous groundwater data, which can be a limitation in data-scarce regions. The SGI, introduced by Tallaksen and van Lanen (2004), provides a standardized approach to track temporal variations in groundwater levels, enabling the identification of drought patterns. Like the GWDI, the SGI relies on consistent and high-quality datasets and necessitates careful interpretation to ensure accurate results.

Hydrological drought has been extensively studied using diverse methodologies. For instance, Sahoo et al. (2015) assessed drought conditions in Haryana and Madhya Pradesh using the Standardized Precipitation Index (SPI), Soil Water Index (SWI), and remote sensing data, linking vegetation conditions to long-term drought trends. Similarly, Ramya et al. (2017) examined drought and groundwater recharge patterns in Karnataka from 1996 to 2016, identifying critical drought years and seasonal variations. Thomas et al. (2017) mapped groundwater scarcity in Ahmadnagar using GIS and thematic layers such as lithology and land use, while Shalini et al. (2012) analysed groundwater variability in Jharkhand, correlating rainfall patterns with seasonal trends and proposing water management strategies.

Despite these advancements, gaps remain in understanding the localized impacts of hydrological drought and the effectiveness of mitigation strategies, particularly in regions with limited data availability. This study aims to address these gaps by analysing hydrological drought using the GWDI and SGI, with a focus on groundwater data. The findings are expected to contribute to the development of adaptive strategies for water conservation, sustainable agriculture, and disaster preparedness, ultimately supporting effective water resource management in drought-prone regions. By integrating insights from previous research and employing robust indicators, this study seeks to enhance resilience to hydrological drought and promote sustainable water use in the face of climate variability.

Objective

- To evaluate hydrological drought conditions based on groundwater levels and delineate meteorological drought risk zones in the Yerla River Basin, Maharashtra.

Study Area

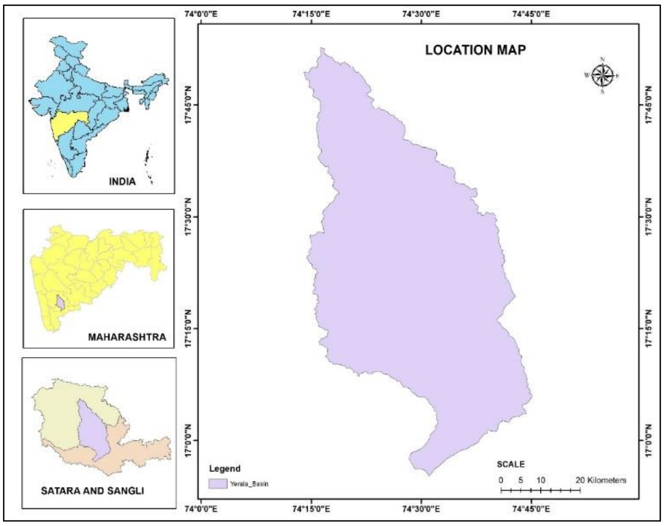

Fig. No. 1: Location Map of the study area

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The Yerla River, a significant tributary of the Krishna River, originates in the Mhaskoba Hills near Manjarewadi Village in Khatav Taluka. Stretching 142.25 km, it flows through the rain-shadow regions of Khatav Taluka in Satara District and parts of Sangli District, including Kadepur, Khanapur, Tasgaon, Palus, and Sangli Taluka, before merging with the Krishna River near Wasagade in Sangli. The river basin spans 3035 km², positioned between 16º50' to 17º50' N latitude and 74º15' to 74º45' E longitude, with elevations ranging from 449 to 1009 meters, bordered by the Vardhangad-Aundh mountains in the west and the Mahimangad mountains in the east. The region has a tropical monsoon climate, with the rainy season occurring from June to September, peaking in July and August, and an annual average rainfall of 597.73 mm (IMD). The geology is primarily basaltic rock, and the area experiences distinct wet (July–October) and dry (January–May) seasons. The Krishna drainage system plays a crucial role in supporting local irrigation, significantly impacting the region's socioeconomic conditions, especially in the economically challenged rain-shadow zones.

Materials and Methodology

A. Data

Groundwater level data from 32 observation wells and piezometers, spanning 1994–2023, were analyzed using Microsoft Excel. Of these, 17 wells are in Satara District (Khatav Taluka and one in Man Taluka), while 14 are in Sangli District (6 in Kadegaon, 7 in Khanapur, and 1 in Tasgaon). Locations and details are shown in Figure 2.

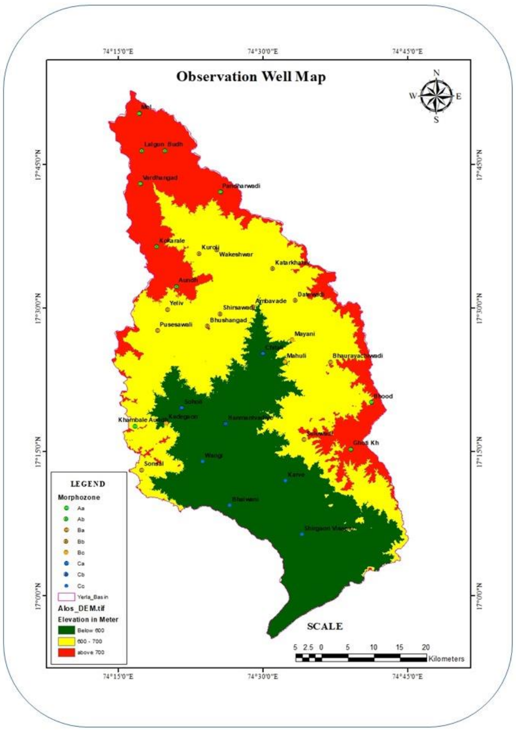

Fig. No. 2: Location map of Observation wells.

B. Methodology:

1. **Hydrological Drought Assessment:**
2. **Groundwater Drought Index (GWDI):** The GWDI is used to quantify groundwater drought conditions by standardizing groundwater level deviations over time. It is calculated as:

GWDIij = (MGWDj – GWDij) / GWDimax

Where, GWDIij = Groundwater Drought Index for ith month and jth year, MGWDj = Mean depth to groundwater table below surface (in meter), GWDij = Depth to groundwater table in ith month and jth year (in meter), and GWDimax = Maximum depth to groundwater table in ith month in available data set for n number of years (in meter).

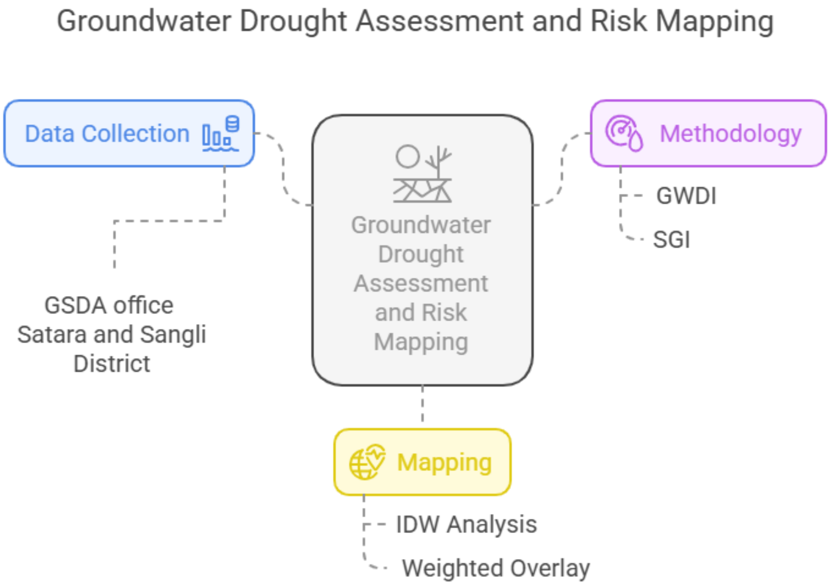

Fig. No. 3: Methodology Chart.

3. **The Standardized Groundwater Level Index (SGI):** SGI, introduced by Tallaksen & Van Lanen (2004), standardizes groundwater level time series to assess groundwater droughts. Modeled after SPI, it is calculated as:

SGI = (W − Wm) / σ

Where W is the recorded groundwater level, Wm is the mean groundwater level, and σ is the standard deviation.

C. Drought Risk zone mapping using IDW and Weightage overlay in ArcGIS 10.4:

The spatial distribution of hydrological drought conditions was analysed using the Inverse Distance Weighting (IDW) interpolation method. IDW estimates drought risk values at unmeasured locations based on the influence of nearby observation points. The process involved collecting GWDI and SGI data, pre-processing, and applying IDW in ArcGIS 10.4 to create drought risk maps. These maps categorized risk levels into normal, mild, moderate, severe, and extreme, showcasing spatial variations in drought severity. A Weighted Overlay Analysis was then performed, combining multiple drought indicators (e.g., GWDI, SGI) with assigned weights to generate a composite map highlighting drought-prone zones, supporting water resource management strategies.

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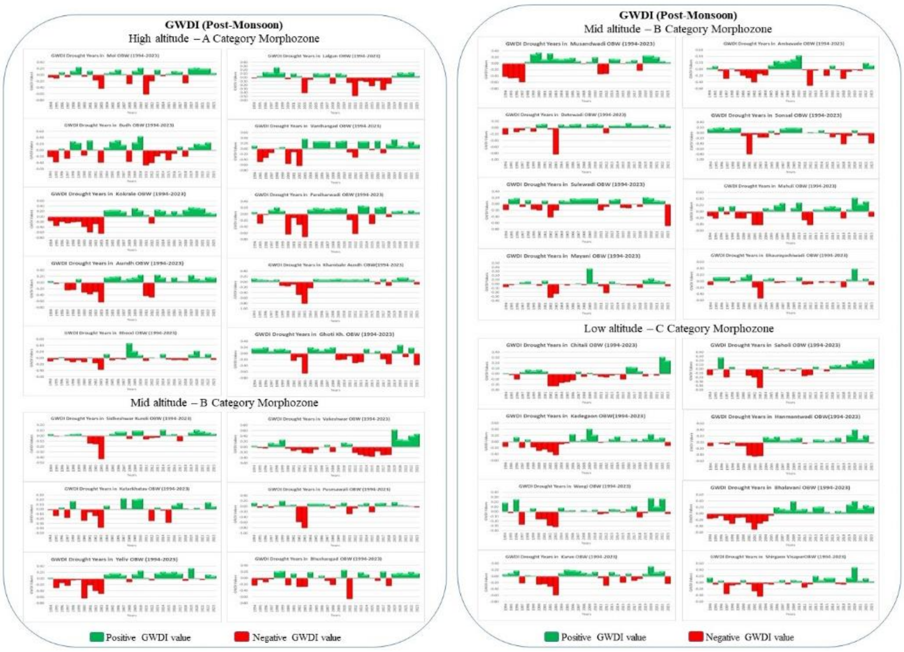
Results and Discussion:

I. Temporal Analysis

1. GWDI (Post-Monsoon)

The Groundwater Drought Index (GWDI) analysis for October from 1994 to 2023 reveals significant drought patterns across 32 observation well villages in the Yerla River Basin. Extreme drought conditions were observed in 2000, 2001, 2002, 2003, and 2011, with October 2003 marking the most severe drought due to deficient southwest monsoon rainfall. Severe drought affected 15 villages across multiple years, while moderate drought was recorded in 25 villages with a 5% frequency. Mild drought occurred in 25 of the 30 years studied, showing a 12% frequency. No drought conditions were reported in years with above-normal rainfall, such as 2005, 2006, 2007, and 2019–2022.



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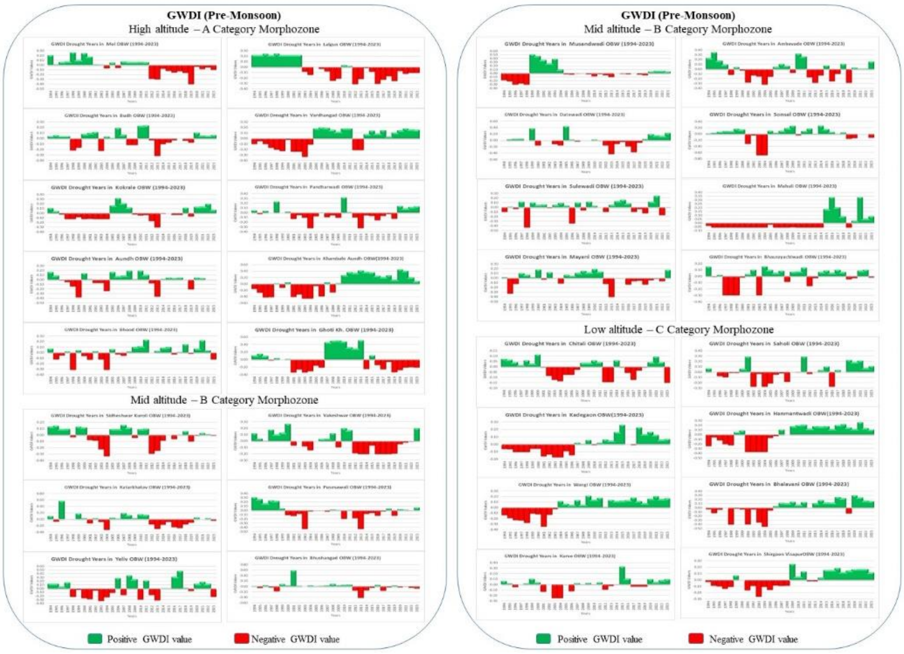

Graph No. 1: Temporal variation of GWDI (Post and Pre-Monsoon) from 1994–2023.

Spatial and temporal variations were evident, with villages like Kadegaon experiencing extreme drought in 2001 (GWDI: -0.79). Critical periods of severe drought were observed in Khambale Aundh and Ghoti Kh. in 2003 and 2002, respectively. These findings underscore the need for early warning systems, sustainable water management practices, and community engagement to mitigate groundwater challenges.

2. GWDI (Pre-Monsoon)

The pre-monsoon GWDI analysis (1994–2023) for the Yerala River Basin highlights significant variations across Sangli and Satara districts. Persistent drought conditions were noted in villages like Hanmantvadiye and Kadegaon from 1994 to 2003, while post-2010, villages such as Ghoti Kh. and Katar Khatav showed recovery due to improved rainfall or management practices. Village-specific trends indicate prolonged drought in Hanmantvadiye until 2005 and severe drought in Khambale Aundh around 2002–2003, with notable improvements afterward. Sonsal recovered after 2009, while Mayani experienced fluctuating conditions with drought peaks in the 1990s. Spatial analysis shows stable groundwater levels in villages like Wangi, while others, such as Saholi and Ambavade, faced recurring droughts. These findings emphasize the need for targeted groundwater management and monitoring to ensure sustainable resource use.

3. SGI (Post-Monsoon)

The Standardized Groundwater Index (SGI) analysis reveals that most villages reported 55–79 normal years, indicating stable groundwater conditions. However, slightly dry years were more frequent in villages like Ghoti Kh., Sulewadi, and Pandharwadi, signaling transitional drought phases. Moderate droughts were more common in Satara district, notably in Ambavade, Bhushangad, and Yeliv, with 9–15 occurrences, while Sangli district reported fewer. Severe droughts were uncommon, affecting villages like Wangi, Saholi, and Bhood,

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while extreme droughts were rare, occurring in Kadegaon, Hanmantvadiye, and Chitali during critical shortages. Sangli's Kadegaon and Khanapur blocks and Satara's Khatav taluka emerged as drought hotspots, whereas villages like Khambale Aundh and Sonsal showed resilience. These findings highlight the need for targeted groundwater management in vulnerable areas, particularly in Kadegaon and Khatav, to mitigate drought impacts.

4. SGI (Pre-Monsoon)

The pre-monsoon SGI analysis (1994–2023) highlights significant drought trends in Sangli and Satara districts. SGI values greater than 1.0 indicate wet conditions, 0.0 to 1.0 denote near-normal, and negative values represent drought severity. Persistent droughts were observed in villages like Hanmantvadiye and Kadegaon, with SGI values below -1.0, especially from 2009 to 2023. Conversely, villages like Sonsal and Shirgaon Visapur showed wet conditions during specific years, such as 2003, with SGI peaking at 3.20. Over time, a transition from wet conditions in the late 1990s and early 2000s to frequent and severe droughts in the 2010s was evident, particularly in 2009, 2015, and 2019. These findings stress the need for sustained groundwater monitoring and management to mitigate recurring drought impacts.

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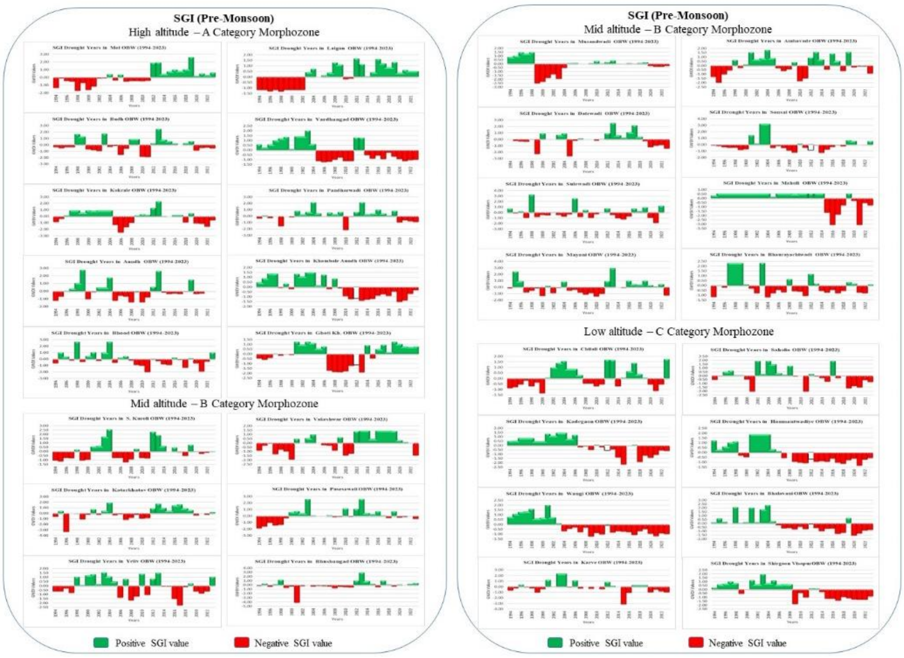
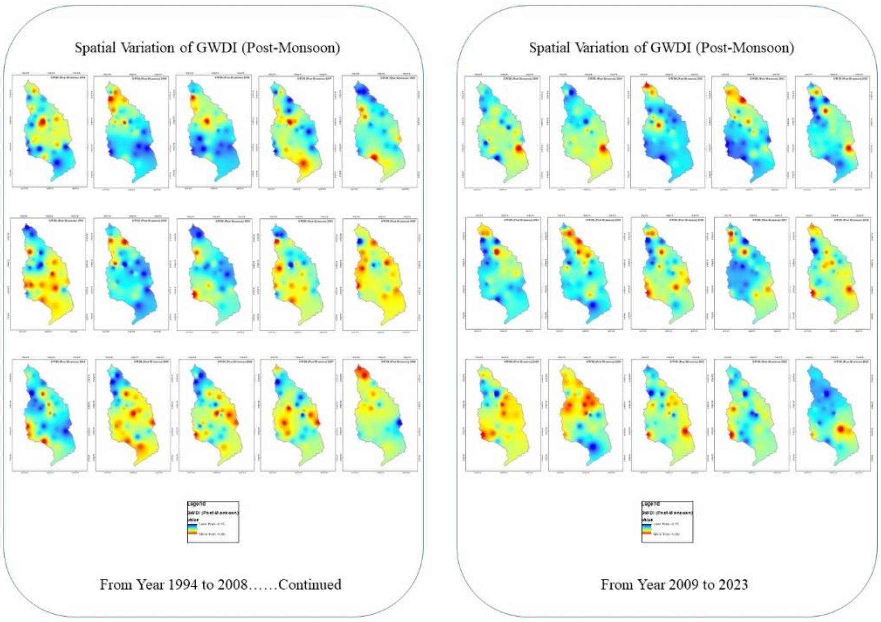


Graph No. 2: Temporal variation of SGI (Post and Pre-Monsoon) from 1994–2023.

II. Spatial Analysis



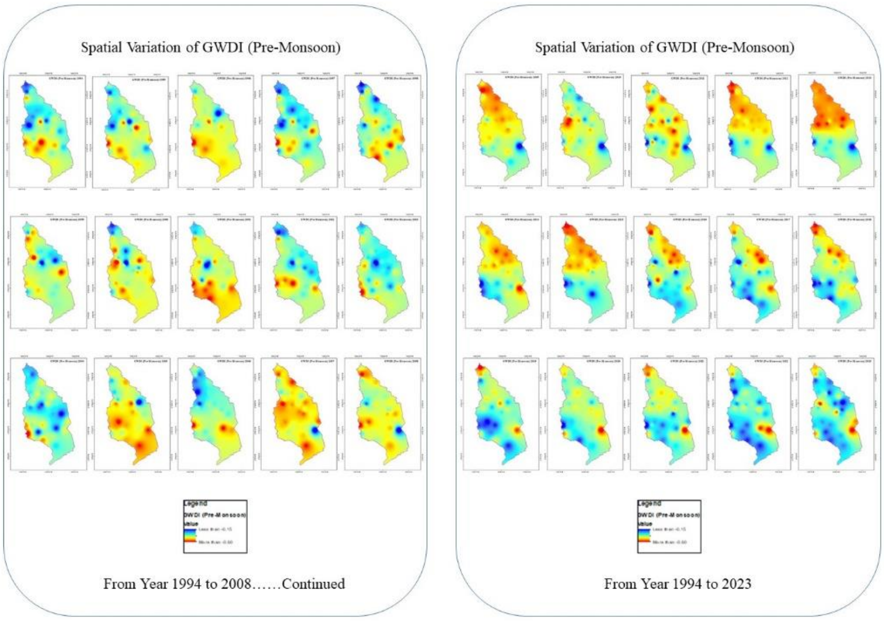


Fig. No. 4: Spatial Analysis of GWDI (Post and Pre-Monsoon) Drought.

1. GWDI (Post-Monsoon)

The GWDI post-monsoon drought frequency analysis (in percentages) shows that most villages experienced predominantly normal years, with S.Kuroli (97%), Bhood (94%), and Chitali (91%) showing the highest stability. Mild drought was notable in Kokarale (30%) and Karve (21%), while several villages, including Hanmantvadiye and Shirgaon Visapur, had only 3%. Moderate drought peaked in Budh (15%), while villages like Khambale Aundh and Bhushangad reported none. Severe drought was rare, with a maximum of 9% in Musandwadi and Vardhanagad, and extreme drought was observed in Pandharwadi (9%) and Vardhanagad (3%). The Sangli district showed higher stability in villages like Khambale Aundh, whereas the Satara district faced more stress in villages like Kokarale and Budh. These findings call for focused groundwater management in vulnerable areas.

2. GWDI (Pre-Monsoon)

The GWDI pre-monsoon analysis reveals that most villages experienced predominantly normal years, with Mahuli (100%) and Chitali (100%) having the highest stability. Mild drought was notable in Musandwadi (24.24%), Yeliv (27.27%), and Ghoti Kh. (27.27%), while moderate drought was significant in Khambale Aundh (24.24%). No severe or extreme droughts were observed, indicating stable groundwater conditions overall. However, Satara district showed milder to moderate droughts, suggesting a need for targeted groundwater management in vulnerable areas like Musandwadi, Yeliv, and Lalgun.

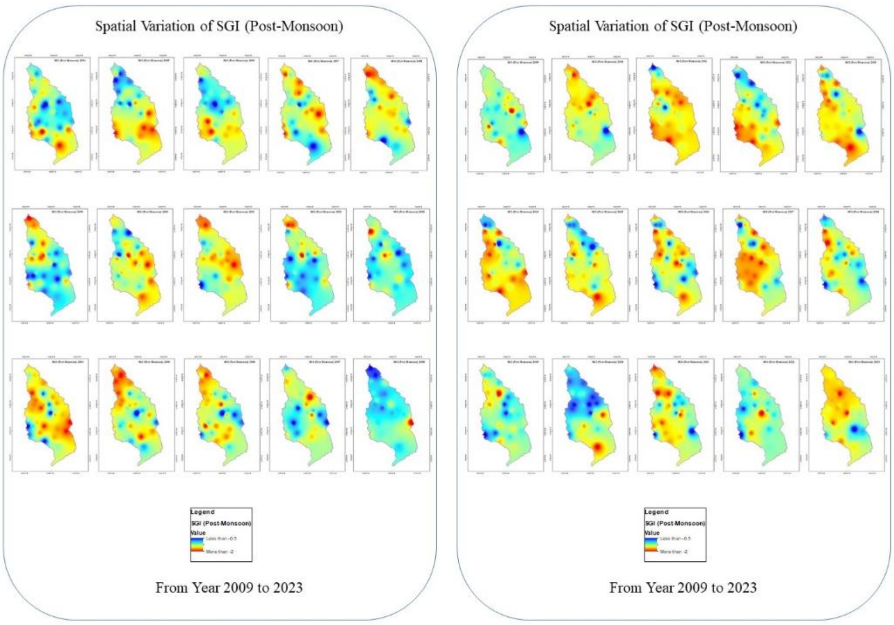
3. SGI (Post-Monsoon)

The SGI post-monsoon drought frequency analysis reveals that the majority of villages in both Sangli and Satara districts primarily experienced normal groundwater conditions. However, several villages faced mild drought conditions, particularly in Sangli (e.g., Ghoti Kh. 42%, Sulewadi 45%) and Satara (e.g., Aundh 30%, Kokarale 30%).

Moderate drought was observed in a few villages, such as Hanmantvadiye (6%), Bhalwani (6%), and Mayani (3%). Severe and extreme droughts were limited but occurred in Hanmantvadiye (3%) and Bhood (3%), highlighting areas where groundwater management may need to be more focused.

4. SGI (Pre-Monsoon)

The SGI pre-monsoon drought frequency analysis indicates a relatively stable groundwater condition in most villages, with normal conditions being predominant across both Sangli and Satara districts. Some villages, such as Hanmantvadiye (33%) and Wangi (33%) in Sangli, experienced mild drought, while moderate drought was more common in areas like Kadegaon (12%) and Shirgaon Visapur (21%). A few villages like Ghoti Kh. (15%) and Pandharwadi (9%) also experienced severe drought conditions. Extreme drought was relatively rare but occurred in Kadegaon (3%), Mahuli (6%), and Pandharwadi (9%). Overall, Sangli and Satara showed a mixed pattern, with mild drought being more frequent compared to severe or extreme drought.



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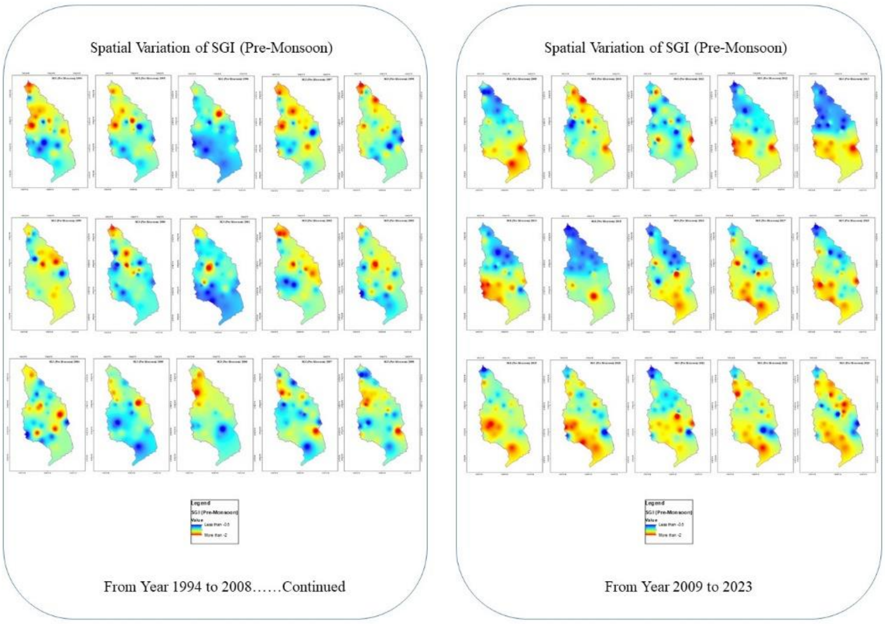

Fig. No. 5: Spatial Analysis of SGI (Post and Pre-Monsoon) Drought.

III. Hydrological Drought Risk Zones

The hydrological drought risk assessment uses the GWDI and SGI to classify drought severity into five categories: extreme, severe, moderate, mild, and normal. The GWDI tracks groundwater level changes in pre-monsoon and post-monsoon periods, while the SGI measures deviations from long-term averages. Both datasets are converted to raster format for spatial analysis with the same resolution. A Weighted Overlay Analysis, assigning equal weights (50% each) to pre- and post-monsoon risk zones, generates a composite map identifying risk zones for water scarcity.

Table No. 1: Classes for Hydrological Drought Risk Assessment Weightage

Drought Category	GWDI	SGI	Assigned Risk Value
Extreme Drought	Below -2.0 meters	SGI ≤ -2.0	5 (Highest Risk)
Severe Drought	-1.5 to -2.0 meters	-1.5 to -1.99	4
Moderate Drought	-1.0 to -1.49 meters	-1.0 to -1.49	3
Mild Drought	-0.5 to -0.99 meters	-0.5 to -0.99	2
Normal Condition	Above 0 meters	SGI ≥ 0	1 (Lowest Risk)

Table No. 2: Hydrological Drought Risk Zone area coverage

Risk Zone	No. of Villages	Area (%)
Normal	19	5.90
Mild	20	7.63
Moderate	42	12.81
Severe	138	50.58
Extreme	78	23.08

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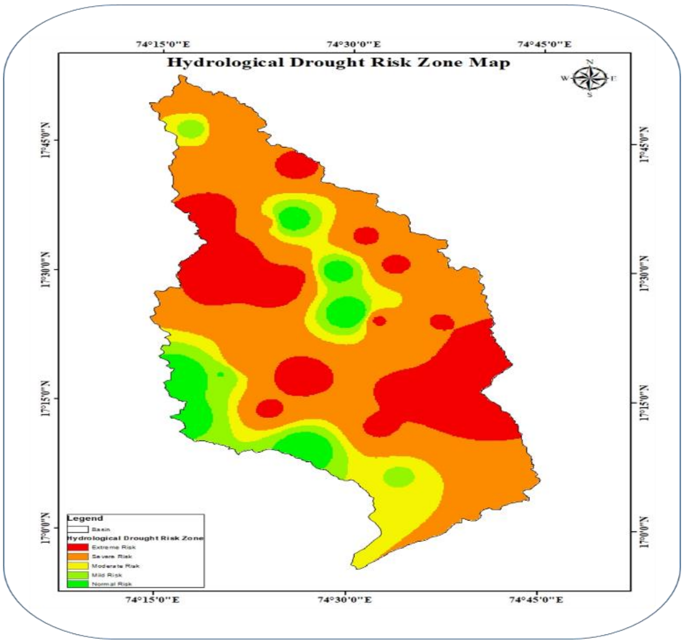
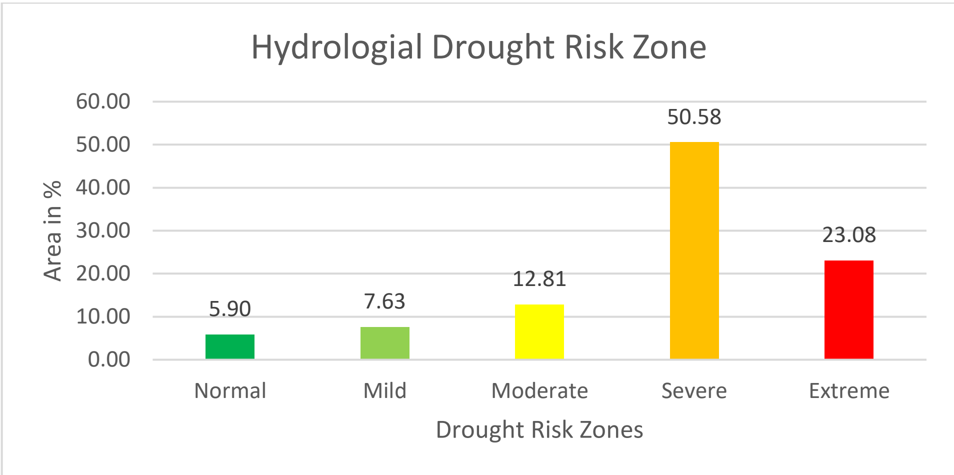


Fig. No. 6: Hydrological Drought Risk Zone Map



Graph No. 3: Hydrological Drought Risk Zone area coverage

The hydrological drought risk assessment reveals that 5.90% (19 villages) fall under the Normal risk zone, indicating stable groundwater levels. The Mild risk zone covers 7.63% (20 villages), showing minor fluctuations, while the Moderate zone, with 12.81% (42 villages), reflects noticeable declines in groundwater levels. A significant portion, 50.58% (138 villages), is classified under the Severe risk zone, where groundwater resources are heavily stressed, requiring urgent interventions. The most critical, the Extreme risk zone, affects 23.08% (78 villages), highlighting severe depletion and the pressing need for effective water management strategies. Together, the Severe and Extreme zones, comprising over 73% of the area, emphasize the urgency of groundwater conservation and proactive drought mitigation efforts.

Conclusion

The study provides a comprehensive analysis of hydrological drought in the Yerla River Basin, Maharashtra, using the Groundwater Drought Index (GWDI) and Standardized Groundwater Index (SGI) from 1994 to 2023. The temporal and spatial analysis reveals significant variations in groundwater levels, with extreme and severe drought conditions observed in multiple years, particularly during periods of deficient monsoon rainfall. Villages like Kadegaon, Hanmantvadiye, and Khambale Aundh emerged as drought hotspots, experiencing prolonged and severe groundwater depletion. Conversely, some villages, such as Sonsal and Wangi, showed resilience and recovery due to improved rainfall or management practices. The hydrological drought risk assessment classified over 73% of the study area into Severe and Extreme risk zones, highlighting the critical need for urgent interventions to address groundwater stress. The findings underscore the importance of continuous monitoring, early warning systems, and sustainable water management practices to mitigate the impacts of hydrological drought on water resources, agriculture, and ecosystems.

Recommendation

Effective groundwater management is crucial for drought-prone villages such as Kadegaon, Hanmantvadiye, and Khatav taluka. Implementing localized recharge measures like rainwater harvesting, check dams, and percolation tanks can enhance groundwater availability. Promoting water-efficient agricultural practices, including drip irrigation and crop diversification, will reduce groundwater dependency. Establishing a real-time groundwater monitoring network, integrating remote sensing and GIS for spatial analysis, will facilitate early drought detection and proactive interventions. Community participation and awareness programs on sustainable water use, watershed development, and afforestation can enhance conservation efforts. Policy interventions should regulate groundwater extraction in over-exploited areas while providing financial and technical support for drought mitigation projects. An integrated approach combining meteorological, hydrological, and socio-economic data is essential for comprehensive drought management, emphasizing adaptive strategies such as drought-resistant crops and alternative water sources. Further research on climate variability and capacity-building programs for stakeholders will ensure long-term water sustainability. Implementing these measures can enhance resilience to hydrological drought in the Yerla River Basin and similar regions.

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