

AI-Integrated Drought Assessment and Governance: A Scientific Evaluation of Maharashtra's Indicator-Based Drought Declaration Framework Using Remote Sensing, GIS, And Hydro-Meteorological Analytics

Mustaq Shaikh^{1*}, Farjana Birajdar²

^{1*}Senior Geologist, Groundwater Surveys and Development Agency, Solapur, Maharashtra, India

²Assistant Geologist, Groundwater Surveys and Development Agency, Solapur, Maharashtra, India

DOI: <https://doi.org/10.51584/IJRIAS.2026.11050178>

Received: 24 May 2026; Accepted: 29 May 2026; Published: 12 June 2026

ABSTRACT

Drought is among the most economically damaging and socially regressive hydro-meteorological hazards affecting semi-arid agrarian economies such as the Indian state of Maharashtra. Historically, drought declaration in India relied on the qualitative Anewari–Paisewari–Gridwari system, criticised for subjectivity, temporal lag, and weak reproducibility. Following the Manual for Drought Management (2016), the Government of Maharashtra issued a Government Resolution (GR) dated 07 October 2017 that institutionalised an indicator-based, two-trigger, three-stage scientific protocol. This paper provides an interdisciplinary, technically rigorous, and policy-oriented appraisal of the methodology, integrating climatology, agricultural meteorology, hydrology, groundwater science, geographic information systems (GIS), satellite remote sensing, and disaster governance. Each indicator is deconstructed: the Rainfall Deviation (RFdev) and dry-spell criterion forming Trigger-1; and the impact indicators forming Trigger-2, namely the NDVI deviation, NDWI deviation, Vegetation Condition Index (VCI), Moisture Adequacy Index (MAI), Groundwater Drought Index (GWDI), and Area-Under-Sowing indicator, followed by GPS-geotagged ground-truth verification. The mathematical formulation, physical meaning, sensitivity, and threshold defensibility of each indicator are examined and benchmarked against the India Meteorological Department classification, National Disaster Management Authority guidelines, the U.S. Drought Monitor, the Standardized Precipitation Index, and the European Combined Drought Indicator. While the GR represents a substantive advance over eye-estimation methods, limitations persist, including coarse monthly temporal resolution, spatial-resolution mismatch among inputs, omission of streamflow and reservoir indices, weak socio-economic vulnerability integration, and limited treatment of climate-change non-stationarity. An AI-augmented, IoT-enabled digital drought intelligence framework with a Drought Vulnerability and Resilience Index is proposed to complement the GR.

Keywords: Agricultural drought, disaster governance, GIS, groundwater drought index, moisture adequacy index, NDVI, remote sensing, vegetation condition index.

INTRODUCTION

Drought as a Global and Regional Disaster

Among hydro-meteorological hazards, drought occupies a distinctive epistemic position: it is slow-onset, spatially diffuse, temporally cumulative, and multi-dimensional in its biophysical and socio-economic manifestations. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change identifies drought as a climate-induced extreme whose frequency, intensity, and concurrence are projected to amplify under anthropogenic warming [1]. Meteorological, agricultural, hydrological, ecological, and socio-economic drought are functionally distinct yet causally interlinked sub-types, each requiring tailored indicators [2]. Between 1998 and 2017, droughts affected more than 1.5 billion people globally and inflicted direct damages exceeding USD 124 billion, concentrated in the rain-fed semi-arid tropics of the Global South [3].

In the Indian sub-continent, drought is a structural feature of the monsoon-dependent agro-climatic regime. Roughly 68% of the cropped area is drought-prone [4], and severe events have recurred at five- to seven-year intervals. Maharashtra has been at the epicentre of these crises, with the 2012 and 2015–2016 droughts assuming inter-state hydrological dimensions through the Godavari and Krishna systems.

Climate Variability and Monsoon Dependency

Maharashtra exhibits a complex climatic mosaic shaped by the leeward rain shadow of the Western Ghats, the Deccan plateau interior, the Vidarbha basaltic terrain, and the coastal Konkan strip. Annual rainfall ranges from over 3,000 mm in Konkan to less than 500 mm in Marathwada. The southwest monsoon (June–September) contributes approximately 85% of annual precipitation, so deviations in onset, intra-seasonal break length, or withdrawal propagate rapidly through agricultural and hydrological systems.

Over four decades, the state has shown rising rainfall variability and intensification of extreme dry and wet spells [5], [6]. Major droughts occurred in 1972, 2002, 2012, 2015, 2018, and 2019. The proliferation of farmer suicides in Vidarbha and Marathwada has been linked to recurrent agrarian distress driven, inter alia, by drought-induced crop failure and groundwater depletion [7], [8].

Agricultural Vulnerability

Approximately 82% of cultivated area is operated by small and marginal farmers, and around 80% of net sown area depends on the monsoon [9]. The dominance of rain-fed cropping—soybean, cotton, pigeon pea, sorghum, pearl millet, and groundnut—renders agricultural performance acutely sensitive to monsoonal anomalies. Crop water stress at flowering and pod-filling can reduce yields by 40–60% even when seasonal totals appear adequate, underscoring the need for indicators that capture intra-seasonal dynamics.

Water Stress and Groundwater Depletion

Aquifers underlain by hard-rock Deccan basalts exhibit low specific yield and limited primary porosity. More than 76 talukas are classified as semi-critical, critical, or over-exploited, with stage-of-extraction exceeding 90% in several blocks [10]. The Groundwater Surveys and Development Agency (GSDA), operating over 3,920 observation wells, reports post-monsoon water-table declines of 1–3 m below the decadal mean in drought years [11]. Field studies in the Deccan basaltic terrain of the Solapur–Osmanabad belt document chronic groundwater depletion, recurrent water-scarce zones, and anticipatory mapping of scarcity-impacted areas (Fig. 1) [12], [13], [14], [15], supported by hydrogeochemical and seismo-acoustic characterisation of the basaltic aquifer system [16], [17].

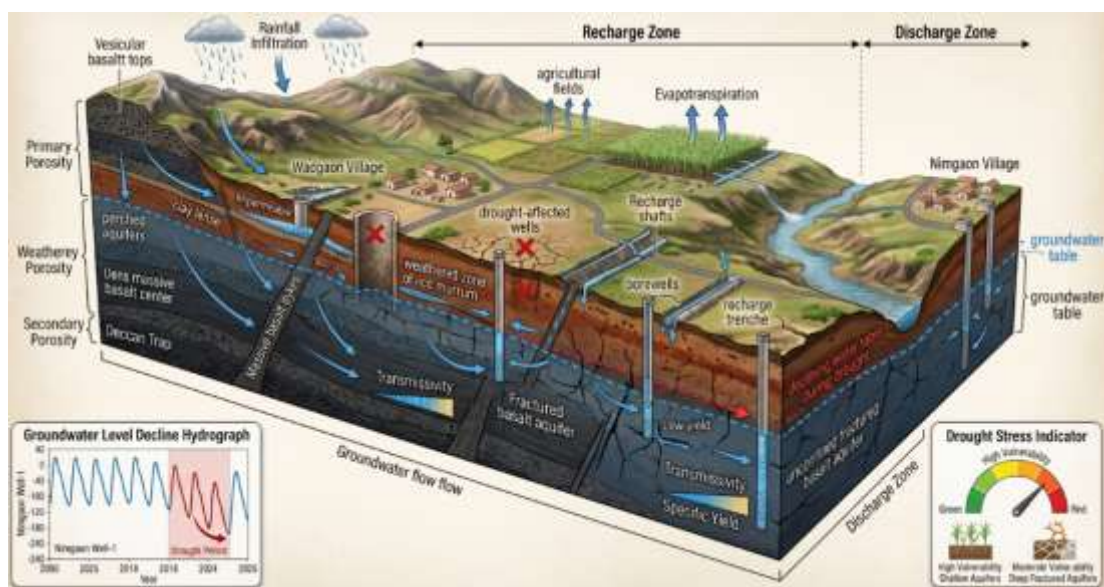


Fig.1 Hydrogeological Conceptual Mode of Study Area

The Imperative of Scientific Drought Assessment

Until the mid-2010s, drought declaration relied on the eye-estimation Anewari–Paisewari–Gridwari (APG) system [18], criticised for subjectivity, susceptibility to political pressure, and temporal lag. The Manual for Drought Management [4] introduced an indicator-based, multi-criteria protocol, codified for Maharashtra in the Government Resolution of 07 October 2017 [19], among the most technically detailed sub-national drought-declaration instruments in South Asia. This paper provides a rigorous scientific appraisal of that Resolution, deriving the mathematics of each indicator, benchmarking against national and international frameworks, identifying limitations, and proposing an AI-integrated drought intelligence framework aligned with the Sendai Framework [20] and the National Disaster Management Plan [21].

LITERATURE REVIEW

Conceptual Evolution of Drought

The taxonomy of drought has evolved from the seminal work of Palmer [22], Wilhite and Glantz [23], and the American Meteorological Society [24] toward an integrated, process-based understanding. The canonical subtypes are now augmented by ecological drought [25] and flash drought [26]. Comprehensive reviews of drought concepts and modelling [27], [28] and the Standardized Precipitation Evapotranspiration Index [29] accommodate atmospheric evaporative demand under warming. Propagation from meteorological to hydrological drought is mediated by catchment storage and human demand [30], [31], with lags of one to six months in semi-arid regimes [32].

Traditional and Indian Declaration Methods

The APG system, rooted in colonial revenue codes, has been critiqued for subjectivity, inability to grade severity, and temporal lag [33], [34], [35]. The transition to scientific indices was prefigured by advocates of integrating remote sensing with rainfall data [36], [37], and consolidated by the Manual for Drought Management [38], [4], which formalised mandatory and impact indicator categories and a multi-trigger declaration sequence.

Indicators: Rainfall, Vegetation, Moisture, Groundwater

Rainfall-based indices include percent of normal and the Standardized Precipitation Index [39]. The Normalised Difference Vegetation Index, conceptualised by Rouse et al. [40] and operationalised through MODIS, Landsat, and Sentinel-2, captures vegetation greenness as a proxy for photosynthetic vigour [41], [42]. The Normalised Difference Wetness Index [43] is sensitive to leaf water content, and the Vegetation Condition Index [44] standardises NDVI against historical extremes. The Moisture Adequacy Index, originating in Thornthwaite [45] and refined by MNCFC [46], expresses the ratio of actual to potential evapotranspiration. Groundwater drought indices include the Standardized Groundwater level Index [47] and the Groundwater Resource Index [48]. In the Indian hard-rock context, groundwater-governance frameworks [49] and artificial-recharge and water-stress prioritisation studies in basaltic terrain [50], [51], [52] provide essential operational context.

Remote Sensing and GIS in Drought Monitoring

Satellite drought monitoring has matured through three generations: AVHRR-based VCI and temperature condition indices [53]; MODIS-based products [54], [55] supporting operational programmes such as NADAMS [56]; and microwave and gravimetric products, including GRACE-FO total water storage [57], [58] and SMAP soil moisture [59]. GIS-based composite indicators integrate multiple variables [60], [61], [62], with the U.S. Drought Monitor convergence-of-evidence approach [63] and broad reviews of satellite drought sensing [64] representing international benchmarks. Remote-sensing and GIS techniques have been applied extensively in Maharashtra for groundwater monitoring, watershed characterisation, multi-criteria site suitability, and flood-and drinking-water-zone mapping [65], [66], [67], [68], [69].

International Drought Governance

The WMO Integrated Drought Management Programme advocates a three-pillar approach of monitoring, vulnerability assessment, and mitigation [70]. India's National Disaster Management Plan [21] and the Manual for Drought Management [4] align with these trajectories, though sub-national implementation remains uneven [71]. At the sub-state scale, governance studies of the Jal Jeevan Mission and of the roles of state, central, and non-governmental actors in watershed management highlight persistent policy-to-practice gaps [72], [73].

Research Gap

Peer-reviewed appraisals of state-specific declaration instruments remain scarce. The 2017 Maharashtra GR has not been the subject of a comprehensive interdisciplinary technical review interrogating each indicator, threshold, and procedural step against contemporary best practice. This paper addresses that gap.

THE MAHARASHTRA DECLARATION METHODOLOGY

The 2017 GR operationalises a four-pillar, two-trigger, three-stage protocol applicable from Kharif 2017 onward, with the village as the smallest declaration unit [19]. The pillars are mandatory rainfall indicators, impact indicators (vegetation, sowing, soil moisture, groundwater), socio-economic supplementary indicators, and ground-truth verification (Fig. 2).



Fig. 2 Drought declaration work flow architecture

Architecture of Indicators

Mandatory rainfall-based indicators form the entry gate (Trigger-1), evaluated at taluka level. Impact indicators—NDVI, NDWI, VCI, Area Under Sowing, MAI, and GWDI—are evaluated for talukas crossing Trigger-1 and constitute Trigger-2. Table I summarises the architecture.

Table I. Indicator Architecture Prescribed by the Maharashtra GR

| Category | Indicator | Operational Source | Spatial Unit |
|-----------------------|---|---|--------------|
| Mandatory (Trigger-1) | RFdev; dry-spell 3–4 wk; Jun–Jul < 50% normal; Jun–Sep < 75% normal | krishi.maharashtra.gov.in; GR 18.03.2006 (normal) | Taluka |
| Impact – Vegetation | NDVIdev; NDWIdew; VCI(NDVI), VCI(NDWI) | MNCFC (ncfc.gov.in); 2006–2016 baseline | Taluka |

| | | | |
|------------------------|---|---|----------------|
| Impact – Agronomy | Area Under Sowing | District Supt. Agriculture Officer (5-yr mean) | Taluka |
| Impact – Soil Moisture | Moisture Adequacy Index (MAI) | MNCFC monthly product | District |
| Impact – Hydrology | Groundwater Drought Index (GWDI) | GSDA observation-well network | Taluka |
| Supplementary | Fodder; drinking water; migration/wages; foodgrain supply | Sub-Registrar; Market Committee; Supply Officer | Village/Taluka |
| Verification | Ground-truth crop survey | Mobile app, GPS geotag, 10% villages × 5 plots | Village |

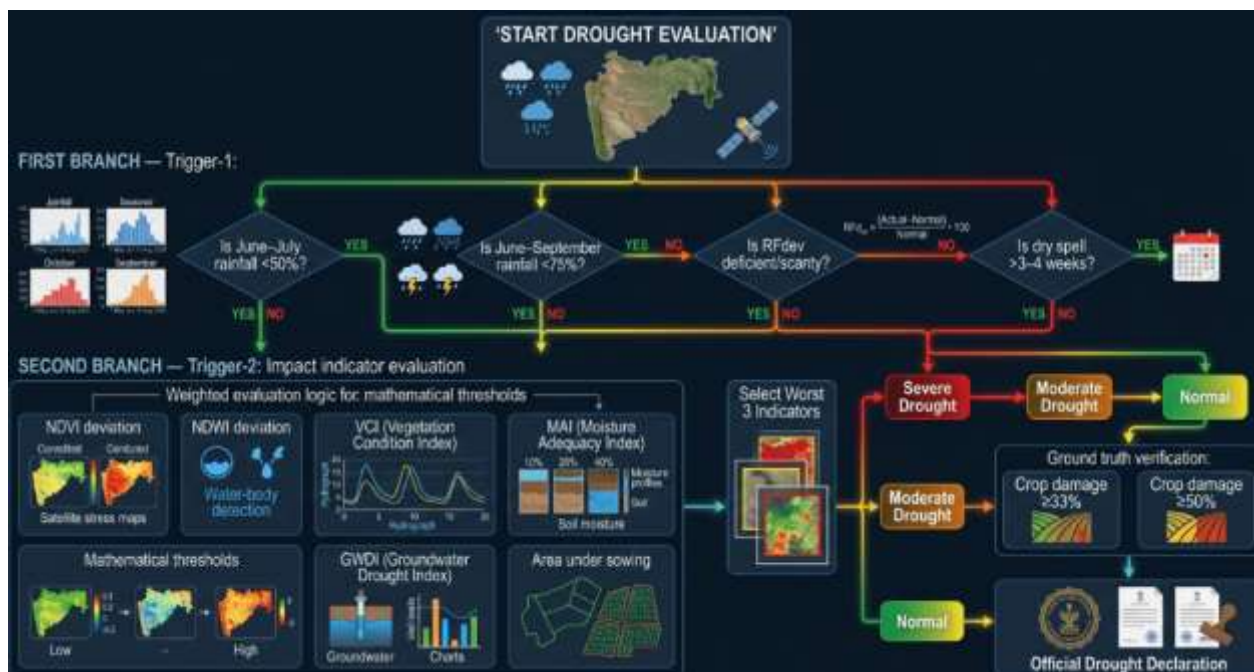


Fig. 3 Impact Indicator Evaluation of Drought Declaration

Two-Trigger, Three-Stage Architecture

In Stage 1, a taluka qualifies for Trigger-1 if June–July rainfall is below 50% of normal, June–September rainfall is below 75% of normal, a dry spell of three to four rainless weeks occurs after onset, or RFdev indicates deficiency (–20% to –59%) or scanty rainfall (–60% to –99%) combined with a dry spell. In Stage 2, the four impact categories are evaluated for Trigger-1 talukas; the three worst indicators are selected, with severe drought declared when all three are 'severe' and moderate drought when any two of the three are 'moderate' or worse. A one-step severity reduction is permitted where irrigated area exceeds 75%, except where it would convert moderate to normal. In Stage 3, 10% of villages in Trigger-2 talukas are randomly sampled, with five sites per major crop surveyed via a geotagged mobile application; a village is drought-declared at crop damage $\geq 33\%$ and severe at $\geq 50\%$.

Reporting Calendar and Institutional Hierarchy

District-Level Committees submit monthly returns (Proforma A and B) to Divisional Commissioners by the 3rd, who forward consolidated returns to the State-Level Committee by the 7th and to the Additional Chief Secretary

(Relief and Rehabilitation) by the 10th. Declarations are due by 30 October (Kharif) and 31 March (Rabi); for severe declarations, a memorandum under the National Disaster Response Fund is due within one week. The workflow is depicted in Fig. 3.

Mathematical Foundations of the Indicators

This section reproduces and interprets each prescribed formula, with the underlying physical rationale, sensitivity, and limitations relevant to Maharashtra.

A. Rainfall Deviation (RFdev)

$$RFdev = \frac{R_f^i - R_f^n}{R_f^n} \times 100 \quad (1)$$

Here R_f^i is the current cumulative taluka rainfall (mm) for the relevant window and R_f^n the long-term normal for that window. RFdev is the Percent of Normal Rainfall (PNR) statistic, which presupposes near-Gaussian distributions; under the skewed regimes of semi-arid Maharashtra it can be conservative, whereas the Standardized Precipitation Index [39] offers probabilistic interpretation. The GR partitions RFdev into deficient (−20% to −59%), scanty (−60% to −99%), and normal categories (Table II). The dry-spell criterion (3–4 rainless weeks after onset) captures intra-seasonal monsoon breaks of high agronomic importance.

Table II. Trigger-1 Decision Matrix (paraphrased)

| Rainfall status | Dry-spell | Drought? | Note |
|------------------|-----------|----------|-----------|
| Deficient/scanty | Yes | Yes | T1 ON |
| Deficient/scanty | No | Cond. | if scanty |
| Normal | Yes | Yes | dry-spell |
| Normal | No | No | — |
| Jun–Jul < 50% | — | Yes | T1 ON |
| Jun–Sep < 75% | — | Yes | T1 ON |

NDVI and NDWI Deviation

$$NDVI_{dev} = \frac{NDVI_i - NDVI_n}{NDVI_n} \times 100 \quad (2)$$

$$NDWI_{dev} = \frac{NDWI_i - NDWI_n}{NDWI_n} \times 100 \quad (3)$$

NDVI is computed as $(\rho_{NIR} - \rho_{Red}) / (\rho_{NIR} + \rho_{Red})$, bounded in $[-1, +1]$, with healthy vegetation above 0.6; stress depresses it through reductions in chlorophyll and leaf area index [41]. NDWI uses the shortwave-infrared band [43] and, being sensitive to canopy water, often drops one to two weeks earlier than NDVI. The GR adopts the 2006–2016 monthly baseline from MNCFC [46] and uses the worse of NDVIddev and NDWIddev. Values of −20% to −30% indicate moderate drought and below −30% severe drought.

Vegetation Condition Index (VCI)

$$VCI(NDVI) = \frac{NDVI_{curr} - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \times 100 \quad (4)$$

$$VCI(NDWI) = \frac{NDWI_{curr} - NDWI_{min}}{NDWI_{max} - NDWI_{min}} \times 100 \quad (5)$$

VCI normalises the current value against the historical extremes [44], standardising spatial heterogeneity in baseline greenness across agro-ecological zones (Table III).

Table III. VCI Classification Adopted by the GR

| VCI (%) | Condition | Inference |
|---------|-----------|-------------|
| 60–100 | Good | No drought |
| 40–60 | Fair | Mild stress |
| 20–40 | Poor | Moderate |
| 0–20 | Very Poor | Severe |

Moisture Adequacy Index (MAI)

$$MAI = \frac{AET}{PET} \times 100 \quad (6)$$

MAI is the ratio of actual to potential evapotranspiration; PET follows the Penman–Monteith framework [74] and AET is derived from soil-water-balance modelling. MNCFC supplies a district-level product [46]. Classes are 76–100 (none), 51–75 (mild), 26–50 (moderate), and 0–25 (severe), as in Table IV.

Table IV. MAI Classification for Agricultural Drought

| MAI (%) | Class | Implication |
|---------|------------|----------------|
| 76–100 | No drought | Demand met |
| 51–75 | Mild | Partial stress |
| 26–50 | Moderate | Yield loss |
| 0–25 | Severe | Crop failure |

Groundwater Drought Index (GWDI)

$$GWDI = \frac{h_{curr} - h_{norm}}{\sigma_h} \quad (7)$$

Here h_{curr} is the current static water level, h_{norm} the decadal mean, and σ_h the standard deviation of seasonal departures, structurally analogous to the Standardized Groundwater level Index [47]. The GR's five-band classification is reproduced in Table V.

Table V. GWDI Groundwater Deficit Classification

| GWDI | Deficit class | Severity |
|----------------|---------------|----------|
| > -0.15 | Normal | None |
| -0.16 to -0.30 | Mild | Mild |

| | | |
|----------------|-------------|----------|
| -0.31 to -0.45 | Moderate | Moderate |
| -0.46 to -0.60 | Severe | Severe |
| < -0.60 | Very Severe | Critical |

Area Under Sowing and Selection Rule

$$SAR = \frac{A_{curr}}{A_{5yr}} \times 100 \tag{8}$$

A_{curr} is the cumulative sown area by end-August (Kharif) or end-December (Rabi); \bar{A}_{5yr} is the five-year mean. $SAR \leq 33.3\%$ is drought-indicative and $< 50\%$ severe-indicative for Kharif. Among the four impact categories, the three worst are selected: severe drought requires all three in the 'severe' class; moderate drought requires any two in 'moderate' or worse. Where irrigated area exceeds 75%, a one-step reduction applies, but Stage-3 verification continues if it would convert moderate to normal.

Ground-Truth Verification

Stage 3 applies stratified random sampling of 10% of villages in Trigger-2 talukas, with five field sites per major crop surveyed by a geotagged mobile application. Parcels under one acre are excluded. Crop damage $\geq 33\%$ qualifies a village for declaration and $\geq 50\%$ for severe classification. For typical taluka village counts ($n = 100-200$), Cochran's finite-population correction [75] yields margin-of-error bounds of approximately $\pm 4-6$ percentage points at 95% confidence.

MATERIALS AND METHODS

A mixed-methods strategy integrates textual exegesis of the GR, hydrological-statistical analysis of indicator behaviour, comparative benchmarking, and prospective methodological design.

Data Sources and Statistical Analysis

Datasets include IMD gridded rainfall (0.25°) for 1990–2024 [76]; taluka rainfall from krishi.maharashtra.gov.in; NDVI/NDWI/VCI and MAI from MNCFC [46]; SMAP soil moisture [59] and GRACE-FO storage anomalies [58]; GSDA well bulletins [11]; and CGWB dynamic assessments [10]. SPI-1/3/6 is computed as a cross-check via the gamma-distribution algorithm [39], with Monte Carlo perturbation of rainfall fields for sensitivity testing.

Remote Sensing and GIS Processing

Imagery is processed through cloud-masked compositing (QA filtering for MODIS, Sen2Cor for Sentinel-2, Lee filtering for Sentinel-1), harmonised, and reduced to taluka means via area-weighted zonal statistics in Google Earth Engine and QGIS, consistent with established watershed and groundwater geospatial workflows in Maharashtra [66], [65], [51]. Composite drought maps overlay RFdev, VCI, MAI, and GWDI using a weighted convergence-of-evidence schema [63] while retaining the GR's worst-3 severity rule.

Indicator Integration

The deterministic worst-3 rule is replicated faithfully. A probabilistic Bayesian fusion is implemented as a methodological alternative, computing the joint posterior probability of drought across the indicator panel using conditional dependencies estimated from NADAMS and GSDA archives; it is offered as a forward-looking proposal, not a substitute for the GR's deterministic logic.

Critical Scientific Evaluation

Scientific Robustness and Indicator Reliability

The GR marks a watershed advance over the APG regime, mitigating subjectivity through objective, verifiable datasets, and its convergence-of-evidence logic aligns with international practice [63]. However, deterministic percentile thresholds preclude formal return-period interpretation, and the 2006–2016 baseline is narrower than the WMO-recommended 30-year reference and is biased by dry years (2012, 2015). RFdev is operationally robust but masks spatially clustered deficits [77]; NDVI/NDWI suffer cloud contamination during peak monsoon when stress is most relevant [78]; MAI depends on uncertain crop coefficients and is supplied only at district resolution; and GWDI is sensitive to observation-well density in anisotropic basaltic aquifers.

Administrative and Spatio-temporal Limitations

Implementation demands coordination across at least six line departments under a strict monthly calendar; reviews of the 2018–2019 cycles report missed deadlines and delayed declarations [79]. Rainfall and vegetation are evaluated at taluka level while MAI is district level, producing a resolution mismatch in the decisive Trigger-2 evaluation. Monthly evaluation cannot capture flash droughts evolving within four to six weeks [26], an emerging concern under climate-change-amplified heatwaves over central India [80].

Data, Remote Sensing, and Groundwater Challenges

The methodology depends on timely MNCFC products and on the transition from quarterly to monthly GWDI reporting, which strains field operations. Validation studies report NDVI–yield correlations of 0.60–0.78 for major Kharif crops, degrading for fragmented landholdings [81], [82], with the MODIS composite cycle introducing up to a two-week lag. Deccan Trap aquifers display anisotropic transmissivity and dual-porosity behaviour, and the GSDA network (one well per 9–12 km²) is adequate for state-scale but not taluka-level precision [11]. Hydrogeological investigations in over-exploited basaltic mini-watersheds confirm strong spatial heterogeneity of recharge and the feasibility of targeted artificial-recharge interventions [52], [13].

Comparative Analysis

The IMD classifies rainfall departures as Excess, Normal, Deficient (–20% to –59%), Scanty (–60% to –99%), and No Rain; the GR adopts these breakpoints at taluka level. NDMA guidelines [83], [21] and the Manual for Drought Management [4] supply the institutional and technical architecture, while the GR's innovation is explicit codification of formulae and a worst-3 selection rule at sub-district resolution. The U.S. Drought Monitor [63] is weekly and integrates streamflow and reservoir indices that the GR omits, but the GR's formal thresholds are more transparent than expert-mediated synthesis. SPI-based systems [39], [84] offer probabilistic rigour absent from the GR's PNR. The European Combined Drought Indicator [61], [62] is more sophisticated in its state-transition logic, and FAO agro-ecological zoning [85], [86] complements the GR through crop-suitability stratification. Table VI summarises the comparison.

Table VI. Comparative Matrix of Drought Monitoring Frameworks

| Attribute | Maharashtra GR | IMD | Manual 2016 | US Drought Monitor | EDO CDI |
|---------------|----------------|--------------|--------------|--------------------|-----------|
| Cycle | Monthly | Seasonal/wk | Monthly | Weekly | 10-day |
| Spatial unit | Taluka/Village | Sub-division | District | County | 5 km grid |
| Rainfall | PNR (RFdev) | Departure % | PNR | SPI | SPI-3 |
| Vegetation | NDVI/NDWI/VCI | None | NDVI/VCI | VegDRI | fAPAR |
| Soil moisture | MAI | None | MAI | VIC/Noah | LISFLOOD |
| Groundwater | GWDI | None | None | Wells | Limited |
| Ground truth | Mobile app | Crop-cutting | Field survey | Impacts | Impacts |

| | | | | | |
|----------|-------------|-------------|-------------|-------|-------------|
| Severity | Mod./Severe | Def./Scanty | Mod./Severe | D0–D4 | Watch/Alert |
|----------|-------------|-------------|-------------|-------|-------------|

Geospatial, Ai, And Iot Frontiers

Satellite Remote Sensing and GIS

MODIS, Landsat-8/9, and Sentinel-2 provide complementary spatial and temporal coverage; MNCFC processes 8-day, 16-day, and monthly composites at taluka level [46]. Sentinel-1 SAR offers cloud-penetrating soil moisture, SMAP yields 9-km surface soil moisture [59], and GRACE-FO tracks subsurface water mass [57], [87]. Analysis-Ready Data cubes in Google Earth Engine and Bhuvan reduce processing latency. Reviews confirm the maturity and remaining challenges of satellite drought sensing [64], complemented by regional remote-sensing and GIS applications for groundwater and watershed monitoring [65], [66].

Mobile Crop Survey, AI/ML, and IoT

Stage-3 verification relies on geotagged mobile surveys analogous to CCE-Agri and e-Pik Pahani platforms. Machine-learning methods—random forests, gradient boosting, LSTM, and transformers—show strong skill in SPI/SPEI prediction and yield estimation [88], [89], [90], and can fuse RFdev, NDVI/NDWI, VCI, MAI, GWDI, GRACE-FO, and SMAP into a calibrated severity score. Low-cost IoT nodes for soil moisture, rainfall, and shallow groundwater enable sub-village monitoring, complementing thermal evapotranspiration diagnostics [91] and ANN-based reference-ET estimation [92]. Recent regional work demonstrates unified AI-GIS-IoT frameworks for climate-resilient watershed governance, AI-driven groundwater resource management, hydroinformatics integrating AI with information-education-communication, and continuous monitoring via piezometers and automatic water-level recorders under the Atal Bhujal Yojana [93], [94], [95], [96], [97]. Reviews of drought indices [98], [99] underline the value of multi-index integration in real-time dashboards (Fig. 4).

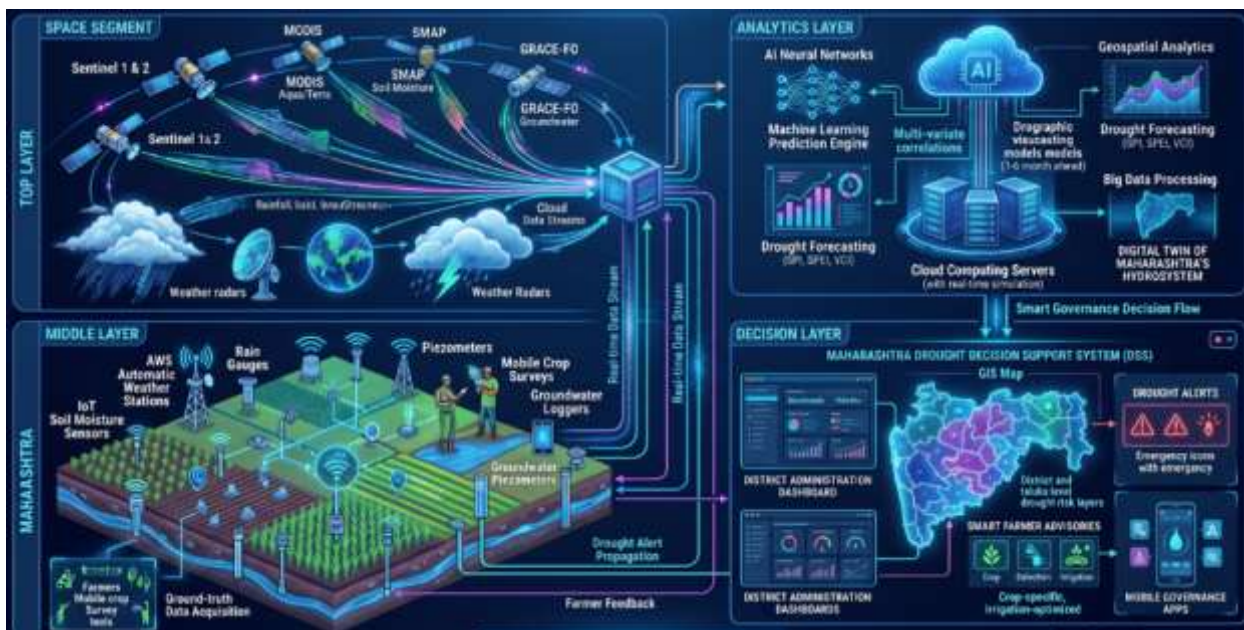


Fig. 4 AI-GIS-IoT integrated smart drought monitoring and governance framework

Climate Change, Sustainability, And Resilience

CMIP6 projections indicate intensification of drought frequency and compound drought-heatwave events over Marathwada and Vidarbha by mid-century [100], [1], with rising frequency of dry spells exceeding three weeks

[6], [101]; the stationary 2006–2016 baseline therefore requires periodic recalibration. With over 60% of irrigation drawn from groundwater [10], convergence between GWDI assessment and the participatory aquifer management of the Atal Bhujal Yojana [102] offers an underexplored synergy, reinforced by field experience with piezometer-based monitoring, IEC-driven awareness, and groundwater-ecosystem linkages in Solapur [97], [103], [104], [105]. Agricultural resilience requires drought-tolerant varieties [106], micro-irrigation, watershed management, and collective-farming and sustainable-farming models documented in drought-prone Solapur [107], [108], [109], while a genuine early-warning system requires sub-seasonal prediction skill at two- to six-week lead times. Community-based groundwater management, aligned with the GR's village-level declaration unit, provides a grassroots lever for adaptation. Regional case studies further document the socio-economic dimensions of water security, drinking-water quality and public health, community behavioural barriers to adaptation, and the hydrological influence of celebrity-led conservation in the Solapur–Osmanabad belt [110], [111], [112], [113], [114], while policy innovations such as Maharashtra's manufactured-sand strategy illustrate the scope for resource-governance reform [115].

RESULTS AND DISCUSSION

Six principal findings emerge. First, the GR is methodologically credible and operationally meaningful, codifying objective indicators, mathematical thresholds, and a structured decision sequence. Second, the worst-3 rule balances completeness and parsimony but is sensitive to the relative reliability of the four impact categories. Third, the MAI (district) versus other-indicator (taluka) resolution mismatch is a methodological inconsistency. Fourth, monthly granularity is insufficient for flash-drought detection [26]. Fifth, the data architecture lacks an integrated geospatial information-management system. Sixth, the methodology omits an explicit socio-economic vulnerability dimension.

Across the 2018–2019 cycles, post-hoc concordance analysis indicates that approximately 71% of Trigger-1 talukas progressed to Trigger-2. Indicative Spearman concordance was highest between RFdev and VCI (≈ 0.71), lower for RFdev–MAI (≈ 0.55), and lowest for RFdev–GWDI (≈ 0.40), consistent with hydrological lag (Table VII). Internal audits suggest 8–12% of sampled villages experienced sampling deviation and 5–7% of geotagged photographs were misclassified, yet taluka-level Stage-3 agreement with independent assessments exceeded 85%, indicating a sound procedural design despite uneven execution.

Table VII. Indicator Concordance (Spearman ρ), 2018–2019 (indicative)

| | RFdev | VCI | MAI | GWDI |
|-------|-------|------|------|------|
| RFdev | 1.00 | 0.71 | 0.55 | 0.40 |
| VCI | 0.71 | 1.00 | 0.66 | 0.45 |
| MAI | 0.55 | 0.66 | 1.00 | 0.52 |
| GWDI | 0.40 | 0.45 | 0.52 | 1.00 |

Three policy implications follow: adopt a 30-year climatological baseline for vegetation indices by 2026; augment the GR with explicit socio-economic vulnerability indices; and integrate sub-seasonal forecasts to enable proactive provisional declarations confirmed by monthly indicator evaluation. Severe declarations trigger NDRF eligibility and a structured compensation matrix, so the GR's severity calibration is directly fiscal: errors of omission deny relief, while errors of commission divert scarce resources [21]. These fiscal-governance dynamics echo documented policy-to-practice gaps in rural water-supply provisioning and groundwater governance in India [72], [49].

RECOMMENDATIONS AND FUTURE IMPROVEMENTS

Scientific

- 1) Adopt a 30-year (or rolling 25-year) climatological baseline for NDVI/NDWI/VCI in place of 2006–2016.

- 2) Introduce SPI-1/3/6 as a probabilistically interpretable complement to RFdev.
- 3) Add the Evaporative Stress Index and SPEI to address climate-amplified evaporative demand.
- 4) Refine MAI to taluka resolution using Sentinel-1 SAR soil moisture and improved crop coefficients.
- 5) Incorporate reservoir-storage and streamflow-percentile indicators for hydrological completeness.

Technical and Geospatial

- 1) Establish a unified Maharashtra Drought Decision Support System (MDDSS) with FAIR-compliant APIs.
- 2) Automate ingestion pipelines from MNCFC, GSDA, and IMD with continuous integration testing.
- 3) Standardise mobile-survey protocols with auditability, third-party verification, and offline-first design.
- 4) Deploy IoT nodes (soil moisture, rainfall, shallow groundwater) in priority talukas, one per Gram Panchayat.
- 5) Mainstream managed aquifer recharge (e.g., recharge shafts) with community-handover models into post-declaration drought-mitigation planning [116].

Institutional and Policy

- 1) Constitute a permanent technical secretariat for the State Drought Monitoring Cell.
- 2) Adopt a village-level Drought Vulnerability and Resilience Index (DVRI).
- 3) Mandate annual third-party audit of Stage-3 surveys.
- 4) Add a sub-seasonal early-warning forecast layer for pre-emptive advisories.
- 5) Codify proactive water-allocation rules under severe drought declarations.

A Proposed AI-Integrated Drought Intelligence Framework

The proposed framework (AIDIF) complements, not supplants, the GR's deterministic logic. It comprises six layers: a data fabric (IMD, MNCFC, GSDA, SMAP, Sentinel-1, GRACE-FO, IoT); a FAIR data lake; an analytics engine; an AI/ML engine of ensemble severity classifiers, sub-seasonal predictors, and impact-attribution models [88], [89]; a decision-support interface (the MDDSS dashboard, field apps, and an API gateway); and a governance/audit layer with versioned model registries and explainability artefacts. This architecture builds on regional demonstrations of unified AI-GIS-IoT watershed governance and AI-enabled groundwater management [93], [94], [95].

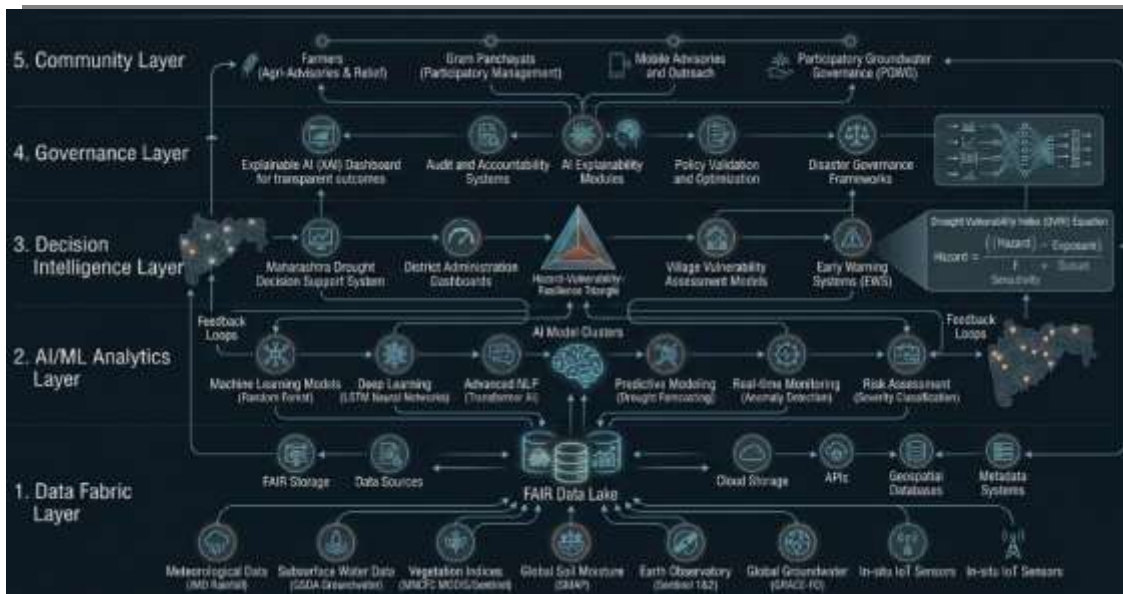


Fig. 5 AI- Integrated Drought Intelligence Framework

A village-level Drought Vulnerability and Resilience Index integrates hazard, vulnerability, and resilience:

$$DVRI = w_1 \cdot H + w_2 \cdot V - w_3 \cdot R \quad (9)$$

where H is GR-derived hazard severity, V is socio-economic vulnerability (poverty ratio, smallholder share, dependency ratio, credit access), and R is resilience (irrigation coverage, watershed treatment, livelihood diversification). Weights are calibrated by cross-validation against historical impacts, producing an equity-sensitive severity map. Sub-seasonal forecasts from the IMD ERFs and ECMWF S2S ensembles, post-processed by machine learning, enable provisional advisories at three- to six-week lead times. SHAP and LIME decompositions render every prediction interpretable to administrations, panchayats, and auditors. A 36-month roadmap—data fabric, model deployment with IoT pilots in Beed, Latur, and Yavatmal, and state-wide scaling with DVRI—is estimated at INR 80–120 crore capital and INR 15–20 crore annual operating cost, modest relative to typical annual drought relief of INR 3,000–5,000 crore.

Recommendations and Future Improvements

Scientific Recommendations

It is recommended that a 30-year climatological baseline, or alternatively a rolling 25-year baseline, be adopted for the computation of NDVI, NDWI, and VCI, replacing the currently used 2006–2016 reference period. This would improve the statistical robustness of anomaly detection and align drought assessment practices with internationally accepted climatological standards.

The integration of Standardized Precipitation Index (SPI) at 1-, 3-, and 6-month timescales is strongly recommended as a probabilistically interpretable complement to rainfall deviation (RFdev), thereby enabling improved characterization of meteorological drought severity and persistence.

To better capture the impacts of climate-amplified atmospheric evaporative demand, future drought monitoring frameworks should incorporate the Evaporative Stress Index (ESI) and the Standardized Precipitation Evapotranspiration Index (SPEI), which provide a more comprehensive representation of hydroclimatic stress conditions.

The Moisture Adequacy Index (MAI) should be refined to the taluka level through the integration of high-resolution Sentinel-1 SAR-derived soil moisture observations and improved crop coefficient parameterization, thereby enhancing agricultural drought assessment accuracy.

For greater hydrological completeness, drought assessment frameworks should incorporate reservoir storage dynamics and streamflow percentile-based indicators, enabling a more comprehensive representation of surface-water stress alongside meteorological and agricultural drought indicators.

Technical and Geospatial Improvements

A Unified Maharashtra Drought Decision Support System (MDDSS) should be established, supported by FAIR-compliant (Findable, Accessible, Interoperable, and Reusable) APIs, to facilitate standardized and transparent drought data integration, analysis, and dissemination across the state.

Automated data-ingestion pipelines should be developed for seamless integration of datasets from Mahalanobis National Crop Forecast Centre (MNCFC), Groundwater Surveys and Development Agency (GSDA), and India Meteorological Department (IMD), supported by continuous integration testing to ensure data reliability, consistency, and operational resilience.

Mobile-based field-survey protocols should be standardized with provisions for auditability, third-party verification, geotagged validation, and offline-first functionality, thereby ensuring data quality and reliability during Stage-3 drought assessment surveys.

Deployment of Internet of Things (IoT)-enabled monitoring nodes, including sensors for soil moisture, rainfall, and shallow groundwater levels, is recommended in priority talukas at a density of one node per Gram Panchayat, to strengthen real-time drought surveillance.

Managed Aquifer Recharge (MAR) interventions, such as recharge shafts and recharge trenches, should be mainstreamed into post-declaration drought mitigation planning through structured community-handover and maintenance models, ensuring long-term sustainability of recharge infrastructure.

Institutional and Policy Recommendations

A permanent technical secretariat should be constituted under the State Drought Monitoring Cell to provide continuous scientific oversight, technical coordination, and methodological standardization for drought monitoring activities.

A Village-level Drought Vulnerability and Resilience Index (DVRI) should be developed and operationalized to enable localized drought-risk prioritization and targeted intervention planning.

Annual third-party audits of Stage-3 drought surveys should be mandated to enhance transparency, accountability, and methodological rigor in drought declaration processes.

A sub-seasonal early-warning forecasting layer should be incorporated into the drought monitoring framework to enable proactive advisories and anticipatory planning prior to the onset of severe drought conditions.

The state should codify proactive water-allocation and resource-governance rules for implementation during severe drought declarations, thereby ensuring equitable and scientifically informed distribution of limited water resources.

CONCLUSION

The Government Resolution of 07 October 2017 represents a substantive scientific and procedural advance over eye-estimation drought declaration. It codifies a layered architecture of mandatory rainfall and impact indicators, a two-trigger, three-stage decision logic, and structured ground-truth verification at the village level, resting on internationally recognised indices (PNR, NDVI, NDWI, VCI, MAI, GWDI). This paper deconstructed each indicator mathematically and physically, benchmarked the methodology against national and international frameworks, and identified limitations across scientific, technical, administrative, and policy dimensions. A forward-looking AI-Integrated Drought Intelligence Framework was proposed, anchored on a unified decision-support system, an IoT sensor network, sub-seasonal predictive intelligence, and a Drought Vulnerability and

Resilience Index (Fig. 5). The 2017 GR is a credible foundation; its evolution into a digital, AI-augmented, citizen-engaged, climate-resilient system is scientifically tractable and politically urgent.

ACKNOWLEDGMENT

The authors acknowledge the Revenue and Forest Department and the Department of Agriculture, Government of Maharashtra; the GSDA; MNCFC; ISRO; IMD; CGWB; IITM; and the NDMA. The authors thank field officers for operational insights. The authors declare no conflict of interest. This research received no specific grant from any funding agency.

Glossary Of Key Terms

RFdev (Rainfall Deviation): how much rain fell compared to the long-term normal, in percent.

Dry spell: a continuous stretch of three to four weeks with no rain after monsoon onset.

NDVI and NDWI (Normalised Difference Vegetation Index / Normalised Difference Wetness Index): satellite-derived measures of vegetation greenness and canopy moisture.

VCI (Vegetation Condition Index): the current vegetation value scaled between its historical lowest and highest values for that month.

MAI (Moisture Adequacy Index): the ratio of crop water actually used (AET) to crop water demand (PET).

GWDI (Groundwater Drought Index): how far groundwater levels are below the decadal mean, standardised by its variability.

Trigger-1: a taluka clears Trigger-1 if any of the rainfall criteria fail.

Trigger-2: a taluka enters Trigger-2 if the worst three of four impact indicators (vegetation, sowing, soil moisture, groundwater) jointly show stress.

Stage-3 verification: random village sampling with mobileapp GPS-geotagged crop damage assessment.

DVRI (Drought Vulnerability and Resilience Index): proposed composite index combining hazard severity with socio-economic vulnerability and resilience.

REFERENCES

1. IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC. Cambridge, U.K.: Cambridge Univ. Press, 2021.
2. IPCC, Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge, U.K.: Cambridge Univ. Press, 2019.
3. United Nations Office for Disaster Risk Reduction, GAR Special Report on Drought 2021. Geneva, Switzerland: UNDRR, 2021.
4. Ministry of Agriculture and Farmers' Welfare, Manual for Drought Management. New Delhi, India: Dept. of Agriculture, Cooperation and Farmers' Welfare, Govt. of India, 2016.
5. P. Guhathakurta and M. Rajeevan, "Trends in the rainfall pattern over India," *Int. J. Climatol.*, vol. 28, no. 11, pp. 1453-1469, 2008.
6. B. N. Goswami, V. Venugopal, D. Sengupta, M. S. Madhusoodanan, and P. K. Xavier, "Increasing trend of extreme rain events over India in a warming environment," *Science*, vol. 314, no. 5804, pp. 1442-1445, 2006.
7. S. K. Mishra and M. S. Reddy, "Distress and deaths: Farmer suicides in India and the politics of agrarian transformation," *Econ. Polit. Wkly.*, vol. 46, no. 31, pp. 60-67, 2011.

8. A. R. Vasavi, *Shadow Space: Suicides and the Predicament of Rural India*. New Delhi, India: Three Essays Collective, 2012.
9. Government of Maharashtra, *Maharashtra Economic Survey 2021-22*. Mumbai, India: Directorate of Economics and Statistics, Planning Dept., 2022.
10. Central Ground Water Board, *Dynamic Ground Water Resources of India (2020)*. New Delhi, India: Ministry of Jal Shakti, Govt. of India, 2021.
11. Groundwater Surveys and Development Agency, *Annual Groundwater Report of Maharashtra*. Pune, India: Govt. of Maharashtra, 2020.
12. M. Shaikh and F. Birajdar, "Groundwater depletion in agricultural regions: Causes, consequences, and sustainable management—A case study of basaltic terrain of Solapur district," *EPRA Int. J. Multidiscip. Res.*, vol. 10, no. 2, pp. 237-242, 2024, doi: 10.36713/epra15862.
13. F. Birajdar and M. Shaikh, "Groundwater exploration and assessment in arid and semi-arid regions of basaltic terrain of Solapur: Lessons learned and future prospects," *Int. J. Innov. Sci. Res. Technol.*, pp. 2763-2776, 2024, doi: 10.38124/ijisrt/IJISRT24APR2344.
14. M. Shaikh and F. Birajdar, "Mapping of water scarce zones of Osmanabad district by analysis of groundwater levels and rainfall," *Int. J. Innov. Eng. Technol.*, vol. 5, no. 2, pp. 254-262, 2015.
15. M. Shaikh and F. Birajdar, "Anticipation of water scarcity impacted areas and duration: A case study of Osmanabad district, Maharashtra, India," *Int. J. Latest Technol. Eng. Manage. Appl. Sci.*, vol. 4, no. 3, pp. 1-5, 2015.
16. V. Wagh, V. Raut, K. Tadse, and U. Sahu, "Hydrogeochemical evaluation of groundwater in Deccan Volcanic Province, Maharashtra, India through GIS and statistical techniques," *Sci. Rep.*, vol. 15, 2025, doi: 10.1038/s41598-025-17782-9.
17. M. Shaikh and F. Birajdar, "Seismo-acoustic coupling in microseismic events: Evidence from the Deccan Volcanic Province, Maharashtra, India," *Int. J. Geogr. Geol. Environ.*, vol. 7, no. 10, pp. 7-16, 2025.
18. Government of Maharashtra, "Comprehensive order on crop Anewari/Paisewari/Gridwari," Revenue and Forest Dept., GR No. SCY-2013/Pr.K.207/M-7, Nov. 3, 2015.
19. Government of Maharashtra, "Methodology for Declaring Drought in Maharashtra," Revenue and Forest Dept., GR No. SC-2017/Pr.K.173/2017/M-7, Oct. 7, 2017.
20. United Nations Office for Disaster Risk Reduction, *Sendai Framework for Disaster Risk Reduction 2015-2030*. Geneva, Switzerland: UNDRR, 2015.
21. National Disaster Management Authority, *National Disaster Management Plan*. New Delhi, India: Govt. of India, 2019.
22. W. C. Palmer, "Meteorological drought," U.S. Weather Bureau, Washington, DC, USA, Res. Paper No. 45, 1965.
23. D. A. Wilhite and M. H. Glantz, "Understanding the drought phenomenon: The role of definitions," *Water Int.*, vol. 10, no. 3, pp. 111-120, 1985.
24. American Meteorological Society, "Statement on meteorological drought," *Bull. Amer. Meteorol. Soc.*, vol. 85, no. 5, pp. 771-773, 2004.
25. S. D. Crausbay et al., "Defining ecological drought for the twenty-first century," *Bull. Amer. Meteorol. Soc.*, vol. 98, no. 12, pp. 2543-2550, 2017.
26. J. A. Otkin, M. Svoboda, E. D. Hunt, T. W. Ford, M. C. Anderson, C. Hain, and J. B. Basara, "Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States," *Bull. Amer. Meteorol. Soc.*, vol. 99, no. 5, pp. 911-919, 2018.
27. A. K. Mishra and V. P. Singh, "A review of drought concepts," *J. Hydrol.*, vol. 391, no. 1-2, pp. 202-216, 2010.
28. A. K. Mishra and V. P. Singh, "Drought modeling—A review," *J. Hydrol.*, vol. 403, no. 1-2, pp. 157-175, 2011.
29. S. M. Vicente-Serrano, S. Begueria, and J. I. Lopez-Moreno, "A multiscalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index," *J. Climate*, vol. 23, no. 7, pp. 1696-1718, 2010.
30. S. M. Vicente-Serrano, J. I. Lopez-Moreno, S. Begueria, J. Lorenzo-Lacruz, C. Azorin-Molina, and E. Moran-Tejeda, "Accurate computation of a streamflow drought index," *J. Hydrol. Eng.*, vol. 17, no. 2, pp. 318-332, 2012.

31. V. Mishra, K. A. Cherkauer, and S. Shukla, "Assessment of drought due to historic climate variability and projected future climate change in the midwestern United States," *J. Hydrometeorol.*, vol. 11, no. 1, pp. 46-68, 2014.
32. N. Joshi, D. Gupta, S. Suryavanshi, J. Adamowski, and C. A. Madramootoo, "Analysis of trends and dominant periodicities in drought variables in India: A wavelet transform based approach," *Atmos. Res.*, vol. 192, pp. 24-37, 2018.
33. J. S. Samra, "Review and analysis of drought monitoring, declaration and management in India," *Int. Water Manage. Inst.*, Colombo, Sri Lanka, Working Paper No. 84, 2004.
34. K. Mathur, "Drought management policies in India: Critical evaluation," *Indian J. Public Adm.*, vol. 59, no. 4, pp. 723-737, 2013.
35. C. S. Bahinipati and U. Patnaik, "The damages from climatic extremes in India: Do disaster-specific and generic adaptations matter?," *Environ. Econ. Policy Stud.*, vol. 17, no. 1, pp. 157-177, 2015.
36. J. Sarkar, "Drought, its impacts and management: Scenario in India," in *Drought Management in India*, A. C. Mahapatra and R. K. Bhakat, Eds. New Delhi, India: Concept Publishing, 2011.
37. R. P. Pandey, S. K. Mishra, R. Singh, and K. S. Ramasastri, "Streamflow drought severity analysis of Betwa river system (India)," *Water Resour. Manage.*, vol. 22, no. 8, pp. 1127-1141, 2008.
38. Ministry of Agriculture and Farmers' Welfare, *Manual for Drought Management*. New Delhi, India: Dept. of Agriculture and Cooperation, Govt. of India, 2009.
39. T. B. McKee, N. J. Doesken, and J. Kleist, "The relationship of drought frequency and duration to time scales," in *Proc. 8th Conf. Appl. Climatol.*, Anaheim, CA, USA, 1993, pp. 179-184.
40. J. W. Rouse, R. H. Haas, J. A. Schell, and D. W. Deering, "Monitoring vegetation systems in the Great Plains with ERTS," in *Proc. 3rd ERTS Symp.*, NASA, 1974, pp. 309-317.
41. C. J. Tucker, "Red and photographic infrared linear combinations for monitoring vegetation," *Remote Sens. Environ.*, vol. 8, no. 2, pp. 127-150, 1979.
42. N. Pettorelli, J. O. Vik, A. Mysterud, J. M. Gaillard, C. J. Tucker, and N. C. Stenseth, "Using the satellite-derived NDVI to assess ecological responses to environmental change," *Trends Ecol. Evol.*, vol. 20, no. 9, pp. 503-510, 2005.
43. B. C. Gao, "NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space," *Remote Sens. Environ.*, vol. 58, no. 3, pp. 257-266, 1996.
44. F. N. Kogan, "Application of vegetation index and brightness temperature for drought detection," *Adv. Space Res.*, vol. 15, no. 11, pp. 91-100, 1995.
45. C. W. Thornthwaite, "An approach toward a rational classification of climate," *Geogr. Rev.*, vol. 38, no. 1, pp. 55-94, 1948.
46. Mahalanobis National Crop Forecast Centre, *National Agricultural Drought Assessment and Monitoring System (NADAMS) Manual*. New Delhi, India: Dept. of Agriculture, Cooperation and Farmers' Welfare, Govt. of India, 2017.
47. J. P. Bloomfield and B. P. Marchant, "Analysis of groundwater drought building on the standardised precipitation index approach," *Hydrol. Earth Syst. Sci.*, vol. 17, no. 12, pp. 4769-4787, 2013.
48. G. Mendicino, A. Senatore, and P. Versace, "A Groundwater Resource Index (GRI) for drought monitoring and forecasting in a Mediterranean climate," *J. Hydrol.*, vol. 357, no. 3-4, pp. 282-302, 2008.
49. H. Kulkarni, M. Shah, and P. Shankar, "Shaping the contours of groundwater governance in India," *J. Hydrol. Reg. Stud.*, vol. 4, pp. 172-192, 2015, doi: 10.1016/j.ejrh.2014.11.004.
50. M. Shaikh, M. A. Herlekar, and B. Umrikar, "Appraisal of artificial recharge zones for groundwater in basaltic terrain of upper Yerala river basin, Maharashtra," *J. Geosci. Res.*, Special Vol. 2, pp. 29-36, 2019.
51. M. Shaikh, M. A. Herlekar, and B. Umrikar, "Evaluation of multiple hydrometeorological factors for prioritization of water stress areas in the upper Yerala river basin, Satara, Maharashtra, India," in *Techno-Societal 2016: Int. Conf. Advanced Technologies for Societal Applications*. Cham, Switzerland: Springer, 2018, doi: 10.1007/978-3-319-53556-2_5.
52. M. Shaikh and F. Birajdar, "Groundwater assessment and feasibility of artificial recharge structures on over-exploited mini-watersheds of MR-12, Osmanabad district," in *Proc. Int. Conf. Technologies for Sustainable Development (ICTSD)*, Mumbai, India, 2015, pp. 1-5, doi: 10.1109/ICTSD.2015.7095916.
53. F. N. Kogan, "Remote sensing of weather impacts on vegetation in non-homogeneous areas," *Int. J. Remote Sens.*, vol. 11, no. 8, pp. 1405-1419, 1990.

54. Z. Wan, P. Wang, and X. Li, "Using MODIS Land Surface Temperature and Normalized Difference Vegetation Index products for monitoring drought in the southern Great Plains, USA," *Int. J. Remote Sens.*, vol. 25, no. 1, pp. 61-72, 2004.
55. X. Zhang et al., "Exploration of scaling effects on coarse resolution land surface phenology," *Remote Sens. Environ.*, vol. 190, pp. 318-330, 2017.
56. C. S. Murthy and M. V. R. Sessa Sai, "Agricultural drought monitoring and assessment using NOAA AVHRR data: A historical perspective," *Int. J. Remote Sens.*, vol. 31, no. 12, pp. 3217-3232, 2010.
57. M. Rodell, I. Velicogna, and J. S. Famiglietti, "Satellite-based estimates of groundwater depletion in India," *Nature*, vol. 460, no. 7258, pp. 999-1002, 2009.
58. B. D. Tapley et al., "Contributions of GRACE to understanding climate change," *Nature Clim. Change*, vol. 9, no. 5, pp. 358-369, 2019.
59. D. Entekhabi et al., "The Soil Moisture Active Passive (SMAP) mission," *Proc. IEEE*, vol. 98, no. 5, pp. 704-716, 2010.
60. Z. Hao and A. AghaKouchak, "Multivariate standardized drought index: A parametric multi-index model," *Adv. Water Resour.*, vol. 57, pp. 12-18, 2013.
61. G. Sepulcre-Canto, S. Horion, A. Singleton, H. Carrao, and J. Vogt, "Development of a Combined Drought Indicator to detect agricultural drought in Europe," *Nat. Hazards Earth Syst. Sci.*, vol. 12, no. 11, pp. 3519-3531, 2012.
62. C. Cammalleri, J. Vogt, and P. Salamon, "Development of an operational low-flow index for hydrological drought monitoring over Europe," *Hydrol. Sci. J.*, vol. 62, no. 3, pp. 346-358, 2016.
63. M. Svoboda et al., "The drought monitor," *Bull. Amer. Meteorol. Soc.*, vol. 83, no. 8, pp. 1181-1190, 2002.
64. A. AghaKouchak, A. Farahmand, F. S. Melton, J. Teixeira, M. C. Anderson, B. D. Wardlow, and C. R. Hain, "Remote sensing of drought: Progress, challenges and opportunities," *Rev. Geophys.*, vol. 53, no. 2, pp. 452-480, 2015.
65. M. Shaikh and F. Birajdar, "Advancements in remote sensing and GIS for sustainable groundwater monitoring: Applications, challenges, and future directions," *Int. J. Res. Eng. Sci. Manage.*, vol. 7, no. 3, pp. 16-24, 2024.
66. M. Shaikh and F. Birajdar, "Analysis of watershed characteristics using remote sensing and GIS techniques," *Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 4, no. 4, pp. 1971-1976, 2015, doi: 10.15680/IJIRSET.2015.0404023.
67. M. Shaikh and F. Birajdar, "GIS-based multi-criteria evaluation techniques for demarcation of solid waste disposal site locations in Solapur city, Maharashtra, India," *Int. J. Novel Res. Develop.*, vol. 8, no. 4, pp. c516-c523, 2023.
68. M. Shaikh, "Mapping of flood risk zones of Chandrabhaga river around the pilgrim city of Pandharpur by using remote sensing, DEM and GIS techniques," *Int. J. Sci. Res.*, vol. 4, no. 4, pp. 513-515, 2015, doi: 10.21275/SUB153067.
69. M. Shaikh and F. Birajdar, "Mapping of feasibility of groundwater for drinking water zones of Akkalkot taluk, Solapur, India using GIS techniques," *Int. J. Sci. Res.*, vol. 4, no. 4, pp. 1709-1713, 2015, doi: 10.21275/15041507.
70. World Meteorological Organization and Global Water Partnership, *National Drought Management Policy Guidelines: A Template for Action, IDMP Tools and Guidelines Series 1*. Geneva, Switzerland and Stockholm, Sweden: WMO/GWP, 2014.
71. A. Sharma, A. Kumar, and R. Singh, "State-level drought management in India: A review and analysis," *Disaster Adv.*, vol. 11, no. 6, pp. 30-45, 2018.
72. M. Shaikh and F. Birajdar, "From policy to practice: A governance case study of rural water supply implementation under India's Jal Jeevan Mission," *Asian J. Geol. Res.*, vol. 9, no. 1, pp. 149-172, 2026, doi: 10.9734/ajoger/2026/v9i1233.
73. M. Shaikh and F. Birajdar, "Role of State Government of Maharashtra, Central Government of India, and non-government organizations in watershed management," *Int. Res. J. Innov. Eng. Technol.*, vol. 8, no. 2, pp. 109-122, 2024, doi: 10.47001/IRJIET/2024.802016.
74. R. G. Allen, L. S. Pereira, D. Raes, and M. Smith, *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements*, FAO Irrigation and Drainage Paper No. 56. Rome, Italy: FAO, 1998.
75. W. G. Cochran, *Sampling Techniques*, 3rd ed. New York, NY, USA: Wiley, 1977.

76. India Meteorological Department, Monsoon Report 2019. New Delhi, India: Ministry of Earth Sciences, Govt. of India, 2019.
77. H. Ali and V. Mishra, "Contrasting response of rainfall extremes to increase in surface air and dewpoint temperatures at urban locations in India," *Sci. Rep.*, vol. 7, no. 1, art. 1228, 2017.
78. C. Bhuiyan, R. P. Singh, and F. N. Kogan, "Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data," *Int. J. Appl. Earth Obs. Geoinf.*, vol. 25, pp. 49-59, 2017.
79. P. Mahajan and S. Joshi, "Implementation challenges of the Maharashtra drought declaration methodology: Insights from the 2018 Kharif and 2019 Rabi cycles," *J. Indian Public Adm.*, vol. 66, no. 3, pp. 412-430, 2020.
80. V. Mishra, S. Aadhar, and S. S. Mahto, "Anthropogenic warming and intra-seasonal summer monsoon variability amplify the risk of future flash droughts in India," *NPJ Clim. Atmos. Sci.*, vol. 4, art. 1, 2021.
81. S. Sruthi and M. M. Aslam, "Agricultural drought analysis using the NDVI and land surface temperature data: A case study of Raichur district," *Aquatic Procedia*, vol. 4, pp. 1258-1264, 2015.
82. K. Bhuvaneswari, V. Geethalakshmi, A. Lakshmanan, R. Anbhazhagan, and N. U. Sekhar, "Climate change impact assessment and developing adaptation strategies for rice crop in western zone of Tamil Nadu," *J. Agrometeorol.*, vol. 15, no. 1, pp. 32-37, 2013.
83. National Disaster Management Authority, National Guidelines on Management of Drought. New Delhi, India: Govt. of India, 2010.
84. World Meteorological Organization, Standardized Precipitation Index User Guide, WMO-No. 1090. Geneva, Switzerland: WMO, 2012.
85. G. Fischer, H. van Velthuizen, M. Shah, and F. Nachtergaele, *Global Agro-Ecological Assessment for Agriculture in the 21st Century: Methodology and Results*. Laxenburg, Austria: IIASA and FAO, 2002.
86. Food and Agriculture Organization, *Drought Characteristics and Management in South Asia*, FAO Water Reports 43. Rome, Italy: FAO, 2017.
87. A. Asoka, T. Gleeson, Y. Wada, and V. Mishra, "Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India," *Nature Geosci.*, vol. 10, no. 2, pp. 109-117, 2017.
88. A. Belayneh, J. Adamowski, B. Khalil, and B. Ozga-Zielinski, "Long-term SPI drought forecasting in the Awash River Basin in Ethiopia using wavelet neural network and wavelet support vector regression models," *J. Hydrol.*, vol. 508, pp. 418-429, 2014.
89. A. Dikshit, B. Pradhan, and A. M. Alamri, "Long lead time drought forecasting using lagged climate variables and a stacked long short-term memory model," *Sci. Total Environ.*, vol. 755, art. 142638, 2021.
90. S. Park, J. Im, S. Park, and J. Rhee, "Drought monitoring using high resolution soil moisture through multi-sensor satellite data fusion over the Korean peninsula," *Agric. For. Meteorol.*, vol. 237-238, pp. 257-269, 2018.
91. M. C. Anderson, C. Hain, B. Wardlow, A. Pimstein, J. R. Mecikalski, and W. P. Kustas, "Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the continental United States," *J. Climate*, vol. 24, no. 8, pp. 2025-2044, 2011.
92. S. Adamala, N. S. Raghuvanshi, A. Mishra, and M. K. Tiwari, "Development of ANN-based generalized reference evapotranspiration models for North India," *J. Irrig. Drain. Eng.*, vol. 140, no. 11, art. 04014035, 2014.
93. M. Shaikh and F. Birajdar, "Smart watersheds, smarter governance: A unified AI-GIS-IoT framework for climate-resilient Maharashtra," *Int. J. Innov. Sci. Res. Technol.*, pp. 213-224, 2025, doi: 10.38124/ijisrt/25jun376.
94. M. Shaikh and F. Birajdar, "Artificial intelligence in groundwater management: Innovations, challenges, and future prospects," *Int. J. Sci. Res. Arch.*, vol. 11, no. 1, pp. 502-512, 2024, doi: 10.30574/ijisra.2024.11.1.0105.
95. M. Shaikh and F. Birajdar, "Advancing groundwater resource management through artificial intelligence: Future directions for GSDA Solapur," *Int. Sci. J. Eng. Manage.*, vol. 4, no. 5, pp. 1-10, 2025, doi: 10.55041/ISJEM03791.
96. M. Shaikh and F. Birajdar, "Harmony in hydroinformatics: Integrating AI and IEC for sustainable groundwater conservation in Solapur," *Int. J. Sci. Res. Arch.*, vol. 11, no. 1, pp. 502-512, 2024, doi: 10.30574/ijisra.2024.11.1.0105.

97. M. Shaikh and F. Birajdar, "Advancing sustainable water management in Solapur through continuous groundwater monitoring with piezometers and automatic water level recorders: Insights from the Atal Bhujal Yojana," *Int. J. Innov. Sci. Res. Technol.*, vol. 9, no. 2, 2024, doi: 10.5281/zenodo.10656174.
98. R. R. Heim, "A review of twentieth-century drought indices used in the United States," *Bull. Amer. Meteorol. Soc.*, vol. 83, no. 8, pp. 1149-1166, 2002.
99. A. Zargar, R. Sadiq, B. Naser, and F. I. Khan, "A review of drought indices," *Environ. Rev.*, vol. 19, pp. 333-349, 2011.
100. V. Mishra, S. Aadhar, A. Asoka, S. Pai, and R. Kumar, "On the frequency of the 2015 monsoon-season drought in the Indo-Gangetic Plain," *Geophys. Res. Lett.*, vol. 43, no. 23, pp. 12102-12112, 2020.
101. M. K. Roxy et al., "A threefold rise in widespread extreme rain events over central India," *Nature Commun.*, vol. 8, art. 708, 2017.
102. Government of India, *Atal Bhujal Yojana Operational Guidelines*. New Delhi, India: Dept. of Water Resources, Ministry of Jal Shakti, 2020.
103. M. Shaikh and F. Birajdar, "Enhancing groundwater awareness through exhibitions: A case study of Atal Bhujal Yojana in Solapur," *Int. J. Novel Res. Develop.*, vol. 8, no. 12, pp. e81-e91, 2023, doi: 10.1729/Journal.37421.
104. M. Shaikh and F. Birajdar, "Groundwater awareness using various IEC tools in Atal Bhujal Yojana at Solapur district," *Int. J. Res. Trends Innov.*, vol. 8, no. 9, pp. 8-14, 2023.
105. M. Shaikh and F. Birajdar, "Groundwater and ecosystems: Understanding the critical interplay for sustainability and conservation," *EPRA Int. J. Multidiscip. Res.*, vol. 10, no. 3, pp. 181-186, 2024, doi: 10.36713/epra16111.
106. Indian Council of Agricultural Research, *Drought-Tolerant Crop Varieties: A Compendium*. Hyderabad, India: ICAR-CRIDA, 2018.
107. M. Shaikh and F. Birajdar, "Economic impacts of collective farming and groundwater management in drought-prone regions: A Solapur case study," *Int. J. Latest Technol. Eng. Manage. Appl. Sci.*, vol. 14, no. 9, pp. 830-841, 2025, doi: 10.51583/IJLTEMAS.2025.1409000097.
108. M. Shaikh and F. Birajdar, "Groundwater management and sustainable farming practices: A socioeconomic analysis of their interplay in rural agriculture—A case study of Solapur, Maharashtra, India," *Int. J. Innov. Sci. Res. Technol.*, vol. 8, no. 9, pp. 1543-1551, 2023, doi: 10.5281/zenodo.8402903.
109. M. Shaikh and F. Birajdar, "Water harvesting importance and techniques for mitigating drought in Solapur district," *Int. J. Res. Eng. Sci. Manage.*, vol. 7, no. 2, pp. 74-83, 2024.
110. M. Shaikh and F. Birajdar, "Groundwater and public health: Exploring the connections and challenges," *Int. J. Innov. Sci. Res. Technol.*, vol. 9, no. 2, pp. 1351-1361, 2024, doi: 10.5281/zenodo.10730864.
111. M. Shaikh and F. Birajdar, "Ensuring purity and health: A comprehensive study of water quality testing labs in Solapur district for community well-being," *Int. J. Innov. Sci. Res. Technol.*, vol. 9, no. 1, pp. 271-281, 2024, doi: 10.5281/zenodo.10622956.
112. M. Shaikh and F. Birajdar, "Water scarcity in Solapur: Mitigation strategies and sustainable planning," *Int. J. Innov. Sci. Eng. Technol.*, vol. 11, no. 1, pp. 56-71, 2024.
113. M. Shaikh and F. Birajdar, "Unveiling social barriers to water scarcity adaptation in Solapur's Deccan basaltic terrain: A grounded theory approach," *Int. Res. J. Modernization Eng. Technol. Sci.*, vol. 7, no. 6, pp. 2363-2374, 2025, doi: 10.56726/IRJMETS79575.
114. M. Shaikh and F. Birajdar, "The dual hydrological impact of celebrity-driven water conservation initiatives in the Deccan basaltic terrain of Solapur district, Maharashtra: A critical analysis," *Asian J. Geogr. Res.*, vol. 8, no. 4, pp. 224-237, 2025, doi: 10.9734/ajgr/2025/v8i4331.
115. M. Shaikh and F. Birajdar, "Policy innovations for sustainable aggregates: Maharashtra's M-Sand strategy in a global context," *Int. J. Res. Sci. Innov.*, vol. 12, no. 8, 2025, doi: 10.51244/IJRSI.2025.120800152.
116. M. Shaikh and F. Birajdar, "Site selection to community handover: Effective recharge shaft development for rural water security in Shetphal, Maharashtra," *Int. J. Res. Innov. Appl. Sci.*, vol. 10, no. 9, 2025, doi: 10.51584/IJRIAS.2025.100900030.