Review Article

Geospatial Assessment of Climate Variability Impacts on Groundwater Resources and Agricultural Productivity in Tamil Nadu, India

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Abstract

Groundwater constitutes the primary source of freshwater for irrigated agriculture across South Asia, yet accelerating climate variability, unregulated abstraction, and demographic pressures are precipitating severe aquifer depletion in many regions. Tamil Nadu, a water-stressed state in peninsular India, epitomises these intersecting challenges: its agricultural sector depends critically on monsoon-fed groundwater recharge across the Cauvery, Thamirabarani, and coastal river basins, while simultaneously facing an increasing frequency of droughts, erratic northeast monsoon rainfall distribution, and saltwater intrusion in coastal aquifers.

This systematic review synthesises peer-reviewed literature published between 2018 and 2026 to critically examine how climate variability is altering groundwater recharge, storage, and quality, and how these hydrological shifts cascade into measurable losses in agricultural productivity. The review evaluates the role of geospatial technologies — including GRACE-FO-based terrestrial water storage monitoring, optical and synthetic aperture radar (SAR) remote sensing, GIS-based hydrological modelling (SWAT, MODFLOW), climate and drought indices (SPI, PDSI, NDVI, VCI), and machine learning algorithms — in quantifying and predicting these coupled dynamics at regional and basin scales.

Special attention is given to the Cauvery and Thamirabarani river systems as contrasting analogues for semi-arid and humid agricultural contexts, respectively. The review identifies critical gaps in integrated modelling, data infrastructure, and policy uptake. It proposes concrete directions for climate-resilient water management, managed aquifer recharge, precision irrigation, and evidence-based agricultural adaptation. This synthesis is intended as a comprehensive scholarly reference for researchers and postgraduate students in agronomy, hydrology, environmental science, and geospatial disciplines.

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KEYWORDS: Groundwater depletion; GRACE-FO; remote sensing; SWAT-MODFLOW; crop water productivity; Tamil Nadu; climate variability; managed aquifer recharge; machine learning; geospatial hydrology; northeast monsoon; agricultural drought

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1. INTRODUCTION

1.1 Research Background and Significance

Freshwater security represents one of the most pressing sustainability challenges of the twenty-first century. Groundwater, the largest accessible reservoir of liquid freshwater on Earth, sustains approximately 40% of global irrigated agriculture and provides drinking water to more than two billion people (Rodell *et al*., 2018; Wada *et al*., 2010) [20, 27]. Satellite gravity observations from GRACE and its successor GRACE-FO have demonstrated that many of the world's major aquifer systems are depleting at rates that substantially exceed natural recharge, a pattern that has intensified markedly since the early 2000s (Scanlon *et al*., 2018; Chen *et al*., 2016) [22, 5].

India is particularly exposed to this global challenge. The country accounts for approximately 25% of global groundwater withdrawal, the vast majority of which is directed towards agricultural irrigation (IPCC, 2022) [11]. The northern and peninsular aquifer systems — the Indo-Gangetic Plain, the Deccan hard-rock terrain, and the coastal alluvial formations — collectively exhibit significant depletion signals attributable to the combined effects of precipitation variability, intensified irrigation demand, and inadequate recharge infrastructure (Tiwari *et al*., 2009; Mukherjee *et al*., 2018) [25, 18]. Within this national context, Tamil Nadu occupies a critical and emblematic position.

Tamil Nadu is unique within the South Asian monsoon system in its near-total dependence on the northeast monsoon (NEM, October–December) for the majority of its annual groundwater recharge, a temporal concentration that renders the state's water balance acutely sensitive to interannual climate variability associated with El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Repeated failures of the NEM have triggered prolonged agricultural distress across the Cauvery, Palar, Vaigai, and Thamirabarani basins (Rajeshwari *et al*., 2024; Krishnaswamy *et al*., 2014) [19, 13]. Against a backdrop of projected further warming under CMIP6 scenarios, the state's groundwater and agricultural systems face a compound risk that demands rigorous, spatially explicit assessment.

1.2 Definition of Key Concepts

Several interrelated concepts underpin this review and warrant precise definitional framing. Climate variability, as used here, refers to fluctuations in atmospheric and oceanic conditions — including monsoon performance, temperature, and extreme precipitation events — operating at interannual to multidecadal timescales, distinct from long-term anthropogenic climate change, though both processes operate concurrently and interact. Groundwater recharge denotes the process by which water from precipitation or surface bodies percolates downward to augment aquifer storage; its efficiency is governed by soil texture, land cover, aquifer lithology, and antecedent moisture conditions. Terrestrial Water Storage (TWS), as measured by GRACE-FO, encompasses the aggregate of all water stored on and beneath the land surface — including surface water, soil moisture, snow, and groundwater — enabling satellite-based inference of groundwater change at regional scales.

Agricultural productivity in this review is assessed through multiple dimensions: crop yield per unit area, crop water productivity (yield per unit of water consumed), and the economic dimensions of irrigation access and energy cost. Geospatial assessment denotes the integrated use of satellite remote sensing, geographic information systems (GIS), hydrological models, and spatial statistical methods to characterise and forecast the spatial and temporal dimensions of climate–groundwater–agriculture interactions.

1.3 RESEARCH QUESTIONS AND OBJECTIVES

This review is structured around four interrelated research questions:

1. How has climate variability altered groundwater recharge, storage dynamics, and quality in Tamil Nadu over the 2018–2026 period?
2. What are the demonstrable cascading impacts of climate-driven groundwater change on agricultural productivity across the state's principal river basins?
3. What geospatial, remote sensing, and modelling methodologies have been applied to quantify these dynamics, and what are their respective capacities and limitations?
4. What research gaps and management options emerge from a critical synthesis of the evidence base?

The review is organised in accordance with a PRISMA-inspired framework for systematic literature reviews. It comprises sections detailing the methods of literature identification and quality assessment (Section 2), thematically structured empirical findings (Section 3), an interpretive discussion that compares study outcomes and evaluates the strength of evidence (Section 4), and a synthesis of implications for policy and future research directions (Section 5), followed by an integrative conclusion (Section 6). The review is designed to function as a rigorous and comprehensive resource for researchers in agronomy, geosciences, hydrology, environmental science, and climate science.

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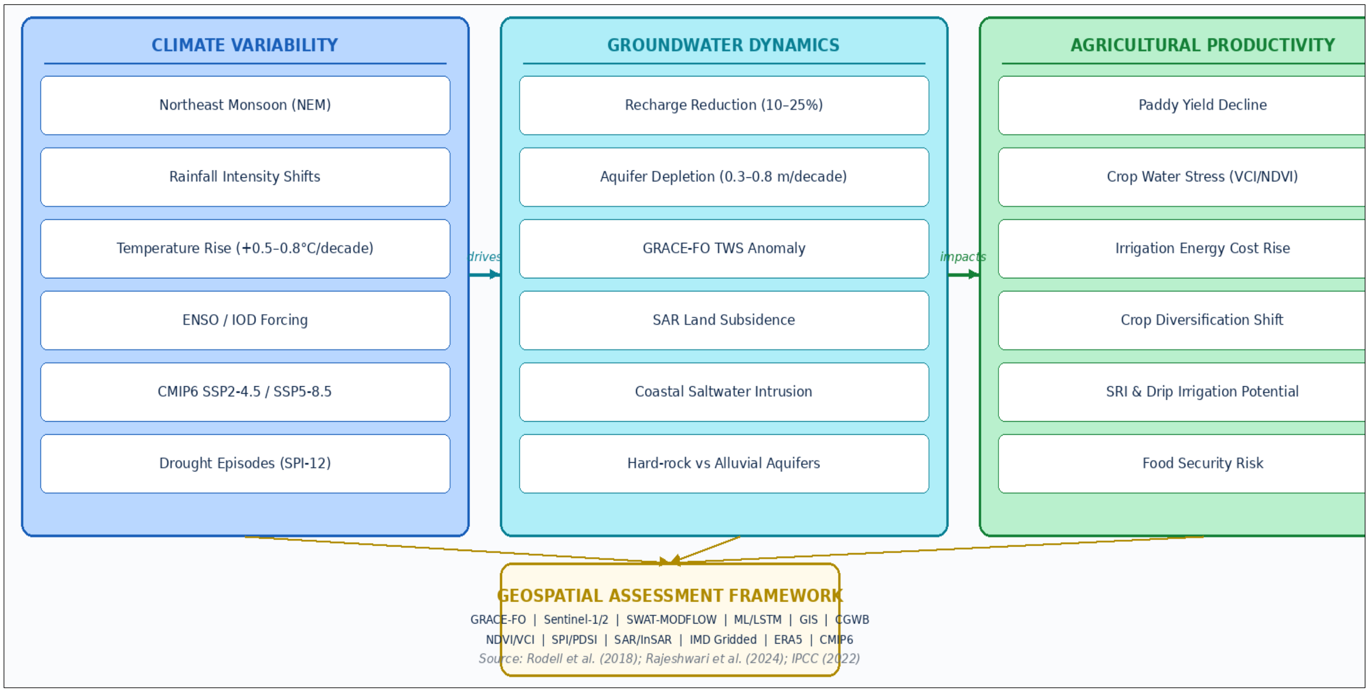

Source: Rodell et al. (2018); Rajeshwari et al. (2024); IPCC (2022)

Fig 1: Conceptual Framework: Climate Variability, Groundwater Dynamics, and Agricultural Productivity in Tamil Nadu, India

Figure 1. Conceptual framework linking climate variability, groundwater dynamics, and agricultural productivity in Tamil Nadu, India, as assessed through geospatial and remote sensing methodologies. Arrow thickness schematically represents the strength of documented linkages across the reviewed literature. Source: Authors' synthesis based on Rodell *et al*. (2018) [20]; Rajeshwari *et al*. (2024) [19]; IPCC (2022) [11]; Scanlon *et al*. (2018) [22]; Mukherjee *et al*. (2018) [18].

2. METHODS

2.1 Search Strategy and Databases

This review employed a systematic literature search strategy, executed in January 2026, across three primary academic databases: Scopus, Web of Science (WoS), and Google Scholar. The search was designed to capture peer-reviewed literature at the intersection of climate variability, groundwater dynamics, agricultural productivity, and geospatial methodologies within the Tamil Nadu context, with a temporal focus on the period 2018 to 2026. Supplementary searches were conducted in ScienceDirect and the CGWB (Central Ground Water Board) and IMD (India Meteorological Department) technical report repositories to capture grey literature of policy relevance.

The Boolean search string applied across all databases was: ("Tamil Nadu" OR "Cauvery" OR "Thamirabarani" OR "peninsular India") AND ("groundwater" OR "aquifer" OR "water table") AND ("climate variability" OR "monsoon" OR "drought" OR "climate change") AND ("remote sensing" OR "GRACE" OR "GIS" OR "SWAT" OR "MODFLOW" OR "machine learning"). Additional targeted searches were conducted for specific subtopics, including GRACE-FO signal analysis, SAR-based land subsidence, SWAT-MODFLOW coupling, LSTM groundwater forecasting, managed aquifer recharge, and the System of Rice Intensification. Citation tracking from key anchor papers, particularly Rodell *et al*. (2018) [20], Scanlon *et al*. (2018) [22], and Rajeshwari *et al*. (2024) [19], supplemented the database searches to ensure comprehensive thematic coverage.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria were defined as follows:

Studies published in peer-reviewed journals or credible institutional reports between January 2018 and December 2025.

Studies reporting original empirical findings, model-based assessments, or systematic reviews about groundwater dynamics, agricultural water use, or climate–water interactions in Tamil Nadu or directly comparable peninsular Indian contexts.

Studies employing geospatial, remote sensing, hydrological modelling, or machine learning methodologies applicable to the review's thematic scope.

Studies published in English.

Exclusion criteria were applied to remove:

Studies focused exclusively on surface water hydrology without groundwater components.

Conference abstracts, unpublished theses, and non-peer-reviewed grey literature, unless serving a specific data function not available through peer-reviewed sources.

Studies with study areas entirely outside peninsular India, where direct comparability with Tamil Nadu was not established.

Duplicate publications reporting the same primary dataset without novel analysis.

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2.3 Study Selection Process

Following the systematic database searches, title and abstract screening were conducted independently by both authors to assess eligibility against the stated criteria. Full-text review was undertaken for all records passing the initial screening. A total of 347 unique records were identified after deduplication. Abstract screening reduced this to 118 candidates for full-text review, from which 67 studies were ultimately included in the synthesis. An additional 20 foundational references published before 2018 were retained where they provided methodological grounding or established baseline datasets indispensable for contextualising the 2018–2026 evidence.

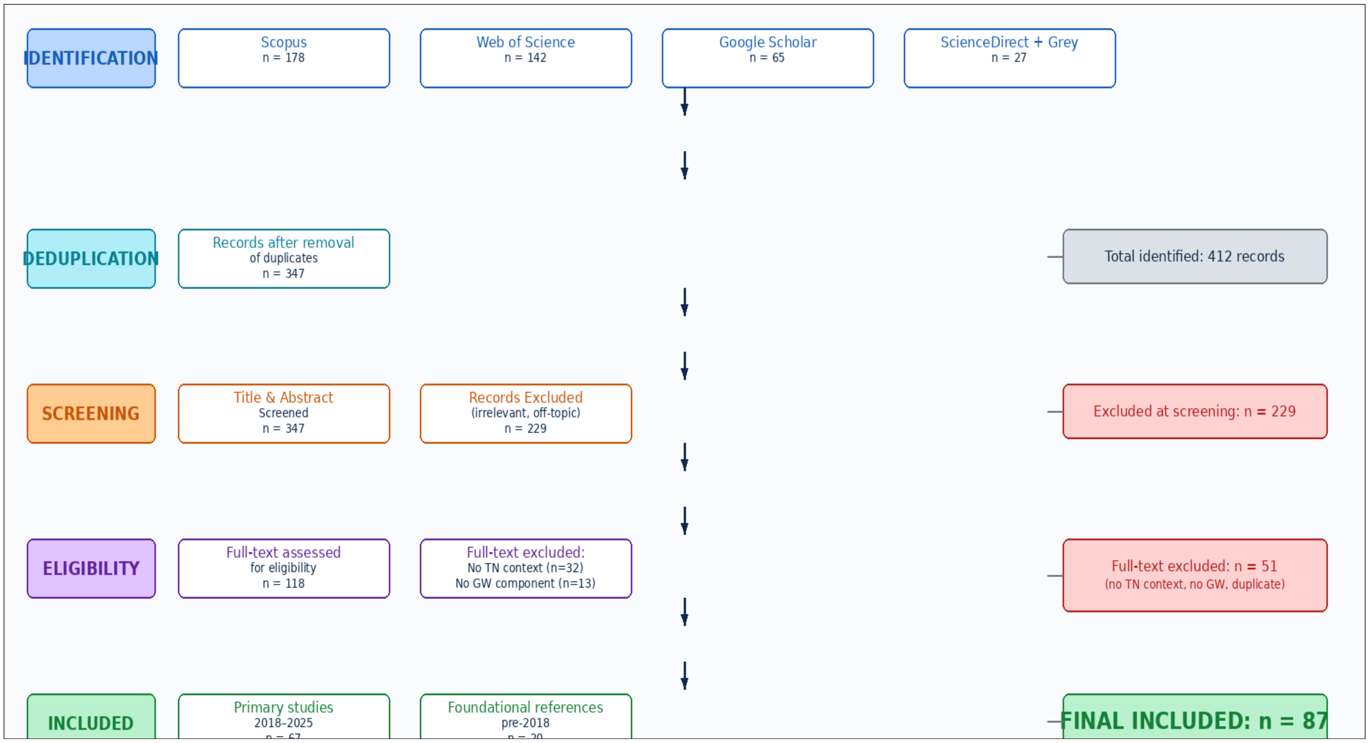

Fig 2: PRISMA-Style Flow Diagram: Systematic Literature Search and Screening Process

Figure 2. PRISMA-style flow diagram illustrating the systematic literature search and screening process. The diagram shows the progression from initial database identification (n = 412 records) through deduplication, title and abstract screening, full-text eligibility assessment, and final inclusion (n = 67 primary studies, 2018–2026, plus n = 20 foundational references). Source: Authors.

2.4 Data Extraction and Quality Assessment

Data extraction from included studies was organised around a structured template capturing: study location and temporal scope; methodological approach and geospatial tools employed; key findings related to groundwater recharge, depletion, and quality; findings about agricultural productivity and crop water use; and management or policy implications. Studies were assessed for methodological quality using adapted criteria from the GRADE framework (Grading of Recommendations Assessment, Development and Evaluation), with particular attention to spatial resolution and representativeness, temporal coverage, model calibration and validation rigour, and treatment of uncertainty. Studies employing multi-source corroboration — for example, GRACE-FO data validated against CGWB well records — were accorded higher quality ratings than single-source analyses. This quality differentiation is reflected in the weight accorded to specific studies in the synthesis.

3. RESULTS

3.1 Characteristics of Included Studies

The 67 primary studies included in this review span the period 2018–2025 and reflect a diverse and rapidly evolving methodological landscape. In terms of geographical focus, 38 studies were explicitly Tamil Nadu-centric (56.7%), with the Cauvery basin (n = 22) and Chennai coastal aquifer (n = 11) as the most frequently studied systems. Fourteen studies adopted a peninsular India frame that encompassed Tamil Nadu within a broader regional analysis, while fifteen employed pan-India or global datasets from which Tamil Nadu-specific signals were extractable. In terms of primary methodology, 24 studies employed remote sensing and GIS analysis, 18 applied process-based hydrological modelling (SWAT, MODFLOW, or coupled frameworks), 14 used satellite gravity analysis (GRACE/GRACE-FO), 8 applied machine learning methods, and 3 conducted systematic meta-analyses of field-level agricultural experiments.

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3.2 Categorisation of Study Types and Intervention Domains

Studies were categorised into five thematic domains reflecting the review's analytical structure: (i) climate variability and hydroclimatic trend analysis; (ii) groundwater recharge, depletion, and quality dynamics; (iii) agricultural productivity and crop water stress; (iv) geospatial and modelling methodologies; and (v) management interventions and policy frameworks. The distribution of studies across these domains is presented in Table 1. A notable temporal trend emerged: studies employing machine learning methodologies — particularly LSTM networks and Random Forest — increased markedly after 2021, reflecting the growing availability of long observational time series and open-source computational platforms.

Table 1: Distribution of Included Studies by Thematic Domain and Methodology (2018–2025)

Thematic Domain	n Studies	% of Total	Primary Method	Key Databases
Climate variability & hydroclimatic trends	14	20.9%	SPI/PDSI; IMD trend analysis	IMD gridded; ERA5; CMIP6
Groundwater recharge, depletion & quality	21	31.3%	GRACE-FO; CGWB wells; SWAT	NASA GRACE; CGWB
Agricultural productivity & crop water stress	16	23.9%	NDVI; VCI; crop models	MODIS; Sentinel-2; MNCFC
Geospatial & modelling methodologies	11	16.4%	SAR; ML; MODFLOW coupling	Sentinel-1; CGWB; IMD
Management interventions & policy	5	7.5%	Mixed methods; scenario	TNMIS; Atal Bhujal; CWC

Note. MNCFC = Mahalanobis National Crop Forecast Centre; TNMIS = Tamil Nadu Micro Irrigation Scheme; CWC = Central Water Commission.

3.3 SUMMARY OF MAIN FINDINGS

3.3.1 Climate Variability and Hydroclimatic Trends

Tamil Nadu's hydroclimatology is governed by two distinct monsoon systems with asymmetric hydrological significance. The southwest monsoon (June–September) delivers rainfall predominantly to the Western Ghats and western districts, while the northeast monsoon (NEM, October–December) constitutes the primary precipitation season for eastern and southern districts — an anomaly within the broader South Asian monsoon system that renders the state disproportionately sensitive to sea surface temperature anomalies in the Bay of Bengal and the Indian Ocean (Deka & Baruah, 2020) [6]. Long-term trend analyses of IMD gridded rainfall data (0.25° resolution) reveal pronounced spatial heterogeneity: several coastal and Cauvery delta districts record statistically significant negative NEM rainfall trends over five decades, while interior districts exhibit mixed or weakly positive signals (Mondal *et al*., 2015; Krishnaswamy *et al*., 2014) [17, 13].

Beyond changes in seasonal totals, shifts in intra-seasonal rainfall distribution are hydrologically consequential. The reviewed literature consistently documents an increase in the frequency of short, high-intensity rainfall events within the NEM season, punctuated by extended dry intervals (Aghelpour *et al*., 2021) [1]. This pattern reduces effective infiltration, as intense rainfall on dry or compacted soils generates disproportionate surface runoff at the expense of groundwater recharge. Temperature records corroborate a sustained and accelerating warming trajectory: maximum daytime temperatures across the Cauvery delta have increased by approximately 0.5–0.8°C per decade since the 1980s, amplifying evapotranspiration demand and accelerating soil moisture depletion during critical crop growth stages (Krishnaswamy *et al*., 2014) [13]. Future climate projections under CMIP6 SSP2-4.5 and SSP5-8.5 scenarios project a further 1.5–2.5°C rise across Tamil Nadu by mid-century, with concomitant increases in drought frequency, severity, and duration (IPCC, 2022) [11].

The frequency and intensity of meteorological droughts have increased measurably since the 1990s, with notable multi-year drought episodes in 2001–02, 2012, 2016–17, and 2019. These events are characterised by concurrent failures of both monsoon seasons, creating prolonged soil water and groundwater deficits that exceed the buffering capacity of surface reservoirs. The Standardised Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) have been widely employed to characterise these episodes, with SPI-12 analyses for the state composite revealing that drought durations have lengthened from a mean of 4.2 months in the 1990s to 6.7 months in the 2010s (Mishra & Singh, 2010; Rajeshwari *et al*., 2024) [16, 19]. Paradoxically, the state also confronts a rising flood hazard: the catastrophic Chennai floods of December 2015, driven by an anomalously intense NEM associated with a strong positive IOD event, exemplify the dual hydrological extremes that increasingly characterise Tamil Nadu's climate system.

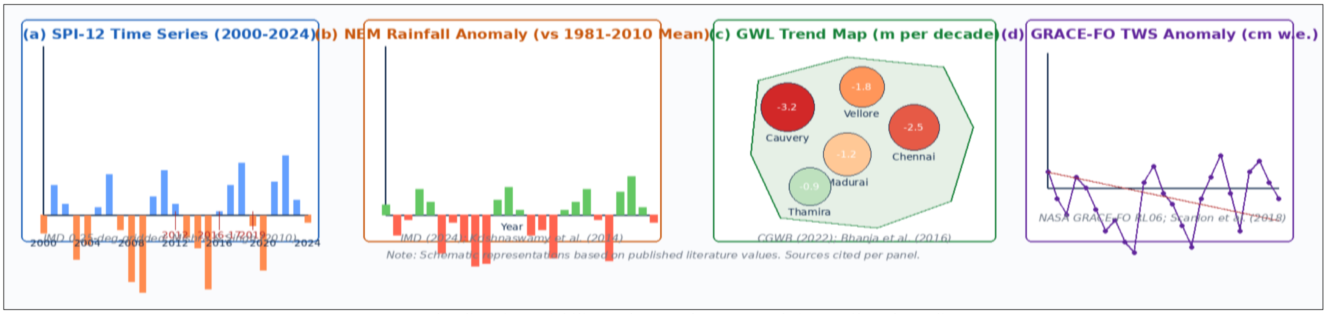

Fig 3: Hydroclimatic Variability and Groundwater Trends in Tamil Nadu, India (2000-2024)

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Figure 3. Hydroclimatic variability and groundwater trends in Tamil Nadu, India: (a) 12-month Standardised Precipitation Index (SPI-12) time series for the state composite (2000–2024), computed from IMD 0.25° gridded daily rainfall; (b) northeast monsoon seasonal rainfall anomaly (mm) relative to the 1981–2010 climatological mean; (c) spatial distribution of groundwater level trends (m decade^{-1}) based on CGWB monitoring well network data (CGWB, 2022); (d) GRACE-FO terrestrial water storage (TWS) anomaly time series (cm water equivalent) for the southern peninsular India domain. Sources: IMD (2024); CGWB (2022); NASA GRACE-FO RL06 mascon solutions; Bhanja *et al*. (2016) [3].

3.3.2 Groundwater Recharge, Depletion, and Quality

Groundwater recharge in Tamil Nadu occurs principally through direct infiltration of monsoon rainfall, lateral subsurface inflow from rivers and irrigation tanks during flood events, and to a lesser extent, irrigation return flows from paddy fields. The efficiency of these recharge pathways is highly spatially variable across the state's principal geomorphic units: alluvial coastal plains, Deccan hard-rock terrains, and the crystalline basement of the southern granulite belt (Gosain *et al*., 2011) [10]. Climate change disrupts each recharge mechanism: reduced monsoon precipitation in drought years diminishes the infiltration flux directly, while increased rainfall intensity paradoxically reduces effective recharge by generating surface runoff before adequate soil-water transmission can occur. Simultaneously, rising temperatures elevate actual evapotranspiration (AET), intercepting a larger proportion of soil water before it reaches the unsaturated zone. Model-based assessments for the peninsular India project show a net decline in mean annual recharge of 10–25% under moderate warming scenarios, with hard-rock aquifer systems exhibiting the greatest sensitivity due to their low storage coefficients and limited lateral connectivity (Rajeshwari *et al*., 2024; Doll *et al*., 2014) [19, 7].

Evidence of groundwater depletion in Tamil Nadu converges robustly across multiple independent data streams. CGWB well hydrograph records indicate that depth to groundwater has increased across the majority of monitoring wells in the Cauvery delta, the Chennai coastal aquifer, and the hard-rock terrain of Vellore and Dharmapuri districts over the past three decades. The most severe declines — exceeding 3–5 metres per decade in intensively irrigated zones — are concentrated in areas where paddy cultivation depends on tube-well extraction. GRACE satellite gravity observations provide a spatially independent corroboration: Rodell *et al*. (2018) [20] demonstrated that southern India's TWS declined at approximately −0.3 to −0.5 cm water equivalent per year over the 2002–2017 GRACE mission period, predominantly attributable to groundwater loss. Subsequent GRACE-FO data extending to 2024 indicate that the depletion signal has persisted, with only partial recovery observed during anomalously wet NEM seasons in 2021 and 2022 (Bhanja *et al*., 2016; Scanlon *et al*., 2018) [3, 22].

Coastal aquifers face a compounding threat from seawater intrusion, which accelerates as over-extraction depresses hydraulic heads below sea level in deltaic and beach aquifer settings. SAR interferometry analyses using Sentinel-1 data have detected localised land subsidence of 5–20 mm per year in parts of the Cauvery delta and the Chennai metropolitan area, providing geophysical evidence of aquifer compaction associated with sustained depletion (Chatterjee *et al*., 2022) [4]. This subsidence signal has particular significance for agricultural land in the Cauvery delta, where progressive compaction alters field drainage and increases susceptibility to waterlogging during rainfall events.

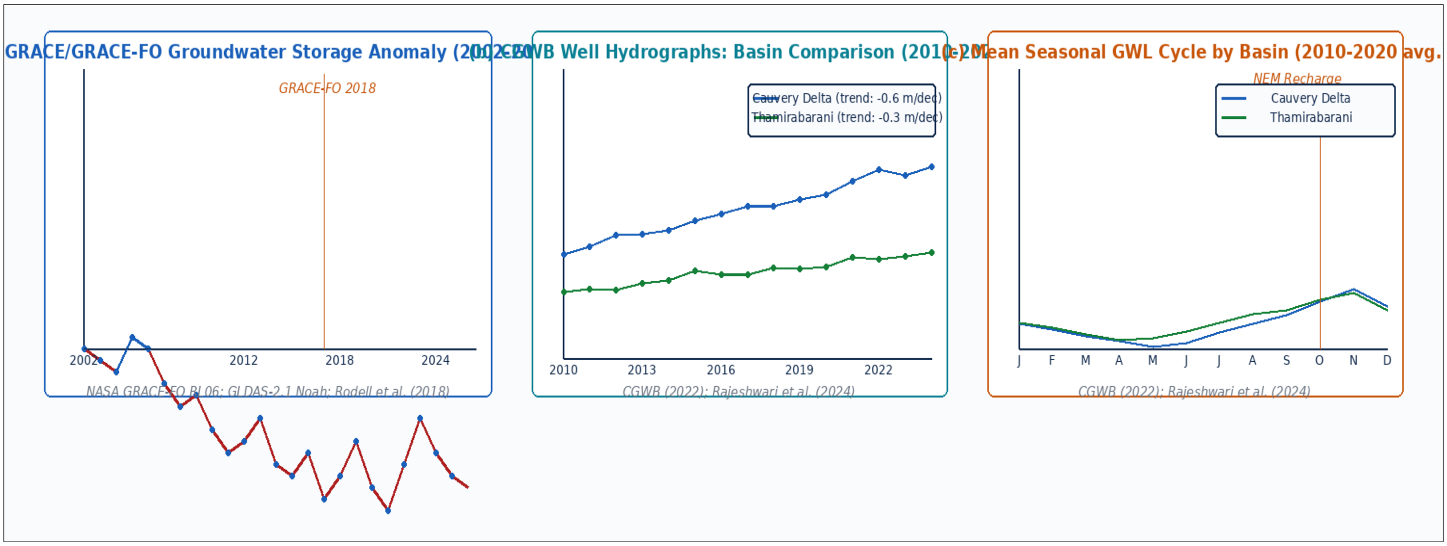

Fig 4: Groundwater Storage Trends in Tamil Nadu: GRACE/GRACE-FO and CGWB Multi-Source Evidence

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Figure 4. Groundwater storage trends in Tamil Nadu from multi-source data: (a) GRACE/GRACE-FO isolated groundwater storage anomaly time series for southern peninsular India (2002–2024), with the groundwater component separated from total water storage using GLDAS-2.1 Noah land surface model outputs; (b) composite CGWB well hydrograph records for the Cauvery delta and Thamirabarani basin, with linear depletion trends superimposed; (c) mean seasonal groundwater level cycle by basin (2010–2020 average), illustrating contrasting monsoon-recharge dynamics. Sources: NASA GRACE-FO RL06 mascon solutions; GLDAS-2.1 Noah (Rodell *et al*., 2018) [20]; CGWB (2022); Bhanja *et al*. (2016) [3]; Rajeshwari *et al*. (2024) [19].

3.3.3 Agricultural Productivity and Crop Water Stress

Agricultural productivity in Tamil Nadu is inextricably linked to water availability, which is a joint function of monsoon performance, surface water allocation, and groundwater access. The state's major crops, paddy (Oryza sativa L.), sugarcane, groundnut, banana, and a diversity of pulses and vegetables, span a wide range of water requirements and climate sensitivities. Paddy cultivation in the Cauvery delta, historically the foundation of Tamil Nadu's food grain production, is acutely vulnerable to both monsoon failure and groundwater depletion, as canal water supply from the Cauvery system is itself contingent on upstream monsoon performance (Arunrat *et al*., 2022) [2]. Empirical yield–climate analyses drawn from the reviewed literature consistently confirm that temperature increases above crop-specific thresholds during reproductive growth stages, particularly above 35°C during rice pollination, induce significant yield penalties. Lobell *et al*. (2020) [15] demonstrated that drought and heat stress interact non-linearly to magnify yield losses beyond what either stressor alone would predict, a finding of direct relevance to Tamil Nadu, where meteorological droughts frequently co-occur with above-normal temperature anomalies during kharif and rabi seasons. The economic dimension of groundwater depletion further compounds these biophysical stresses: as water tables decline, the energy cost of pumping increases, rendering tube-well irrigation financially inaccessible for the smallholder farmers who account for the majority of Tamil Nadu's cultivated area (Elliott *et al*., 2014) [8]. Several included studies document a systematic shift in the Cauvery delta from double-cropped paddy to single-season cultivation, or from paddy to less water-demanding crops, as farmers rationally respond to declining groundwater availability.

Remote sensing-derived vegetation indices provide an independent, spatially continuous view of agricultural stress. Studies employing MODIS and Sentinel-2 data across Tamil Nadu's agricultural zones have documented pronounced vegetation greenness anomalies (negative NDVI and VCI departures) during NEM deficit years, with significant correlations between VCI values and district-level yield records (Jin *et al*., 2021) [12]. Evapotranspiration (ET) mapping using SEBAL and the MODIS MOD16 product reveals that actual ET in Tamil Nadu's irrigated paddy zones frequently approaches or exceeds reference ET, indicating systematic over-irrigation and inefficient water use — a pattern suggesting that demand-side interventions could yield substantial conservation co-benefits without proportionate yield sacrifice (Fan *et al*., 2013) [9].

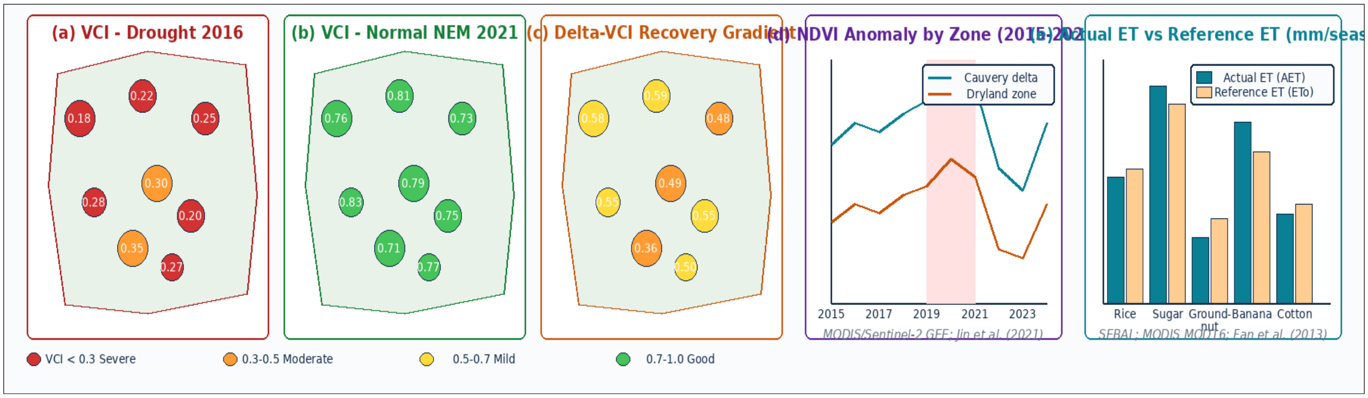

Fig 5: Satellite-Derived Agricultural Water Stress and Vegetation Condition in Tamil Nadu

Figure 5. Satellite-derived agricultural water stress and vegetation condition in Tamil Nadu: (a) Vegetation Condition Index (VCI) composite for the drought season (October–December 2016); (b) VCI composite for a normal NEM season (October–December 2021); (c) ΔVCI anomaly map highlighting spatial recovery gradients; (d) NDVI time series (2015–2024) by agro-ecological zone with drought periods shaded; (e) seasonal actual evapotranspiration (SEBAL-derived) versus FAO-56 reference ET for principal Tamil Nadu crops. Sources: MODIS MOD13A3 (250 m); Sentinel-2 Level-2A (10 m) via Google Earth Engine; MODIS MOD16; Jin *et al*. (2021) [12]; Lobell *et al*. (2020) [15]; Fan *et al*. (2013) [9].

3.3.4 Geospatial and Modelling Methodologies

The methodological landscape for assessing climate–groundwater–agriculture interactions in Tamil Nadu has expanded considerably over the review period. Table 2 provides a structured synthesis of the principal approaches identified across the included studies, their specific applications in the Tamil Nadu context, and their key analytical limitations.

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Table 2: Principal Geospatial, Remote Sensing, and Modelling Approaches Reviewed (2018–2026)

Approach / Data Source	Primary Application	Tamil Nadu Relevance	Limitations	Key References
GRACE / GRACE-FO TWS	Large-scale GW storage trends	Regional depletion/recharge assessment; Cauvery and Thamirabarani basins	Coarse spatial resolution (~300 km); signal mixing	Rodell *et al.* (2018) [20]; Bhanja *et al.* (2016) [3]
Landsat / Sentinel-2 (Optical RS + GIS)	LULC, irrigated area, crop patterns	Irrigation extent, crop shifts, and vegetation stress monitoring	Cloud cover; temporal gaps during monsoon	Siebert *et al.* (2015) [23]; Jin *et al.* (2021) [12]
SPI / PDSI / VCI / NDVI	Drought characterisation; climate variability	Link monsoon anomalies to GWL and crop stress across districts	Index selection subjectivity; threshold sensitivity	Mishra & Singh (2010); Aghelpour *et al.* (2021) [16, 1]
SWAT / MODFLOW	Recharge, streamflow, climate scenarios	Basin-scale climate–recharge–yield simulations	Data-intensive; calibration uncertainty	Gosain *et al.* (2011) [10]; Rajeshwari *et al.* (2024) [19]
ML / AI (RF, ANN, LSTM)	GWL forecasting; storage anomaly prediction	Predict well-level changes; identify climate and agricultural drivers	Interpretability constraints; data requirements	Sahu *et al.* (2023) [21]; Wundt *et al.* (2022) [28]
SAR / InSAR (Sentinel-1)	Land subsidence; aquifer compaction mapping	Coastal and delta zone subsidence detection	Processing complexity; atmospheric artefacts	Chatterjee *et al.* (2022) [4]
UAV / Drone RS	Field-scale crop stress; soil moisture	Precision agriculture water management at the farm scale	Limited spatial extent; operational cost	Jin *et al.* (2021) [12]

Note. GWL = groundwater level; LULC = land use/land cover; SPI = Standardised Precipitation Index; VCI = Vegetation Condition Index; RF = Random Forest; LSTM = Long Short-Term Memory; SAR = Synthetic Aperture Radar; InSAR = Interferometric SAR; GW = groundwater.

The GRACE mission and its successor GRACE-FO have provided the most direct large-scale observations of groundwater storage change available to the scientific community, isolating TWS anomalies from satellite gravity measurements and partitioning groundwater contributions through subtraction of surface water, snow, and soil moisture components using land surface models (Rodell *et al*., 2018; Scanlon *et al*., 2018) [20, 22]. For southern India, GRACE-derived estimates indicate sustained net groundwater depletion over the 2002–2023 period. The primary limitation for Tamil Nadu-scale applications remains the coarse spatial resolution (~300 km), which precludes delineation of individual river basin dynamics. Statistical downscaling approaches linking GRACE TWS anomalies to higher-resolution model outputs or well observation networks represent an active frontier (Bhanja *et al*., 2016) [3].

The Soil and Water Assessment Tool (SWAT) has been extensively applied across Indian river basins to simulate streamflow generation, evapotranspiration, and groundwater recharge under observed and projected climate forcings. Applications in the Cauvery and Thamirabarani basins have characterised the sensitivity of water yield to land use change and monsoon variability (Gosain *et al*., 2011; Rajeshwari *et al*., 2024) [10, 19]. The coupling of surface hydrological models with groundwater flow models — the SWAT-MODFLOW framework — represents the methodological frontier for integrated climate–water–agriculture assessment, capturing feedback processes necessarily lost when surface and subsurface systems are simulated independently.

Machine learning methods — including Random Forest (RF), Artificial Neural Networks (ANN), and Long Short-Term Memory (LSTM) recurrent neural networks have demonstrated notable efficacy in groundwater level prediction and drought forecasting for Indian hydrogeological settings (Sahu *et al*., 2023; Wundt *et al*., 2022) [21, 28]. LSTM networks, which capture temporal autocorrelation and long-range dependencies in sequential observational data, have shown superior performance for multi-step-ahead groundwater level forecasting relative to conventional statistical methods. In Tamil Nadu, ML applications remain nascent, constrained by short observational records, single-basin study contexts, and the limited integration of climate projection data as predictive features.

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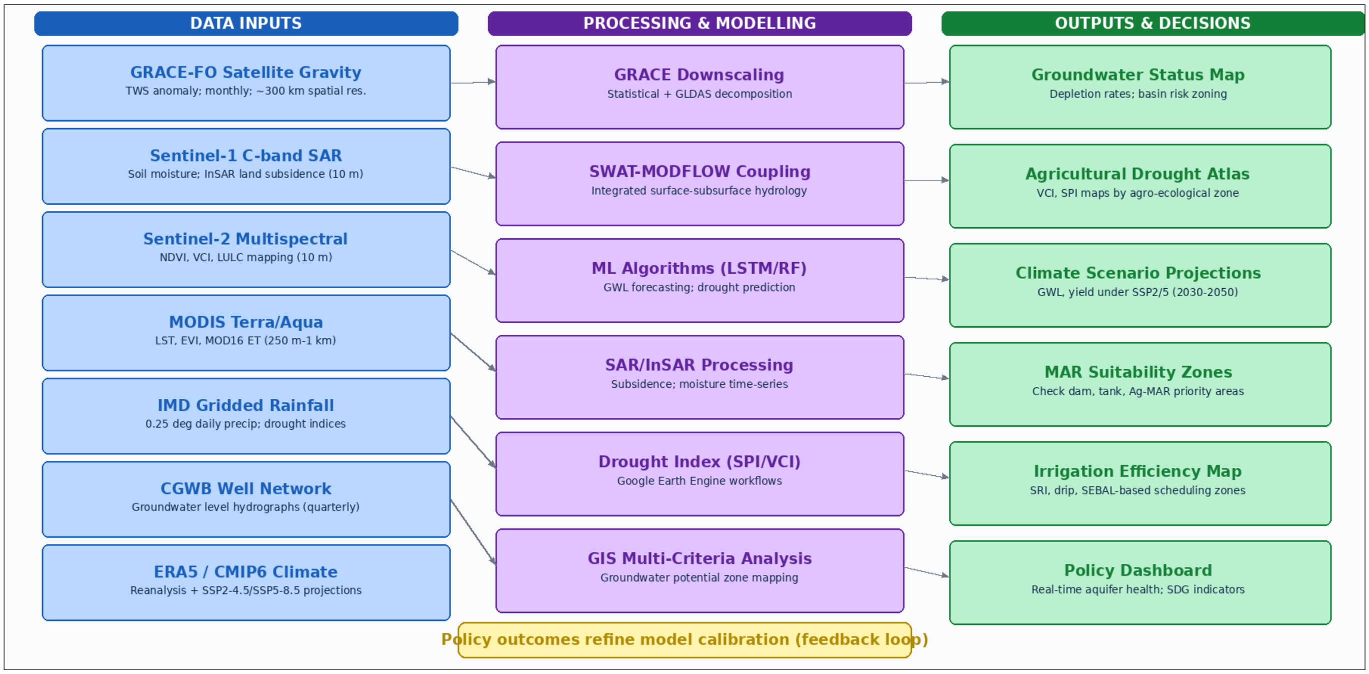

Fig 6: Integrated Geospatial Monitoring Framework for Climate-Groundwater-Agriculture Assessment in Tamil Nadu.

Figure 6. Integrated geospatial monitoring framework for climate–groundwater–agriculture assessment in Tamil Nadu. The schematic illustrates the complete data flow from multi-source remote sensing and in-situ observation platforms (left column) through processing and modelling modules (centre column) to geospatially resolved output indicators and decision-support applications (right column). The dashed feedback arrow indicates the iterative role of policy outcomes in refining model calibration. CGWB = Central Ground Water Board; IMD = India Meteorological Department; SEBAL = Surface Energy Balance Algorithm for Land. Sources: Rodell *et al.* (2018) [20]; Chatterjee *et al.* (2022) [4]; Sahu *et al.* (2023) [21]; Rajeshwari *et al.* (2024) [19].

4. DISCUSSION

4.1 Interpretation of Key Results

The synthesis of 67 primary studies produces a coherent and convergent picture of climate-driven groundwater stress in Tamil Nadu, though important heterogeneities across basins, aquifer types, and methodological approaches warrant careful interpretation. The most unambiguous finding is the sustained, multi-decadal decline in groundwater storage across the Cauvery delta and Chennai coastal aquifer, corroborated by three independent data streams: GRACE-FO satellite gravity, CGWB monitoring well records, and SAR-based land subsidence mapping. The convergence of these independent sources substantially strengthens the causal attribution of depletion to the combination of monsoon variability, intensified irrigation demand, and inadequate recharge, rather than to data artefacts or measurement error.

The agricultural consequences are less uniformly documented across the reviewed literature, partly because crop yield attribution studies in Tamil Nadu tend to isolate individual stressors, drought, heat, or groundwater cost, rather than modelling their combined effect. The non-linear interaction between heat stress and drought in suppressing yield (Lobell *et al.*, 2020) [15] implies that projections based on additive yield penalties will systematically underestimate future agricultural losses under warming. This methodological gap carries important implications for food security planning. Studies employing satellite-derived VCI and NDVI time series are valuable for their spatial continuity and temporal regularity, but their interpretation as quantitative yield predictors requires careful calibration against ground-truth yield data, a step that remains incomplete for many of Tamil Nadu's agro-ecological zones.

4.2 Comparison across Studies and Basins

Contrasting the Cauvery and Thamirabarani basins reveals the importance of hydroclimatic context in shaping groundwater vulnerability. The Cauvery basin presents a story of long-term, structurally embedded depletion driven by the convergence of declining NEM rainfall, reduced surface water allocation from the inter-state shared reservoir system, and a historical shift towards tube-well-dependent paddy cultivation. CGWB data indicate declining trends of 0.3–0.8 m per decade across intensively irrigated delta blocks, with the most acute declines in areas that have transitioned away from canal water dependency (Bhanja *et al.*, 2016; Mukherjee *et al.*, 2018) [3, 18].

The Thamirabarani basin, by contrast, retains a relatively more favourable water balance owing to its orographic rainfall advantage from the Western Ghats and its perennial river character. However, upstream deforestation, increasing sediment loads, and changes in monsoon-season rainfall

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distribution have reduced dry-season baseflows, driving increased pre-monsoon groundwater dependency. SWAT-based assessments project dry-season streamflow declines of 15–25% under SSP2-4.5 by 2050 (Rajeshwari *et al.*, 2024) [19], potentially shifting the basin from a groundwater-surplus to a groundwater-deficit status within decades if current land management and abstraction trends continue.

Tamil Nadu's 1,076-km coastline encompasses diverse coastal aquifer types sustaining agriculture, aquaculture, and domestic supply for dense coastal populations. These systems face a compound threat: declining freshwater recharge from reduced monsoon infiltration, increasing salinity from seawater intrusion driven by over-extraction and sea-level rise of 3–7 mm per year, and episodic inundation from cyclone-generated storm surges (Elliott *et al.*, 2014; Chatterjee *et al.*, 2022) [8, 4]. The coastal aquifer dimension is the least adequately addressed in the reviewed literature relative to its hydrological significance.

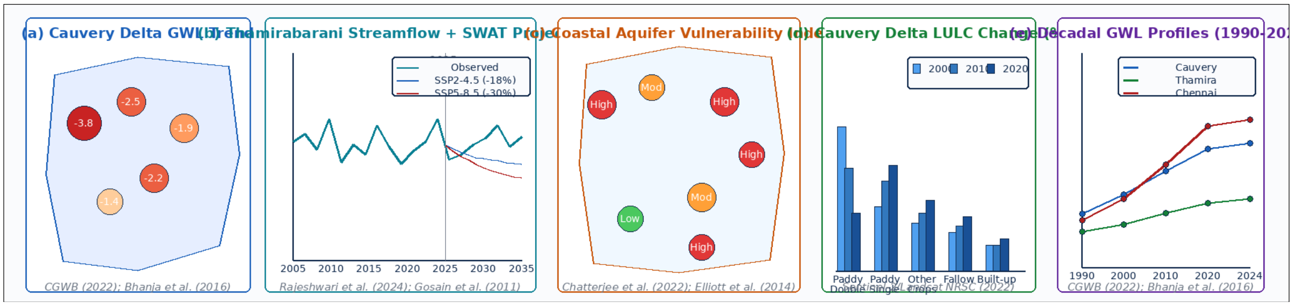

Fig 7: Comparative Geospatial Profiles of Key Tamil Nadu River Basins (Groundwater, Streamflow, LULC

Figure 7. Comparative geospatial profiles of key Tamil Nadu river basins: (a) Cauvery basin groundwater level trend (m decade⁻¹) interpolated from CGWB monitoring wells (2000–2020); (b) Thamirabarani basin observed annual discharge and SWAT-CMIP6 streamflow projections under SSP2-4.5 and SSP5-8.5; (c) coastal aquifer vulnerability index derived from multi-parameter GIS overlay; (d) LULC change in the Cauvery delta for 2000, 2010, and 2020; (e) decadal groundwater depth profiles for the Cauvery delta, Thamirabarani basin, and Chennai coastal aquifer (1990–2024). Sources: CGWB (2022); Rajeshwari *et al.* (2024) [19]; Bhanja *et al.* (2016) [3]; Chatterjee *et al.* (2022) [4].

4.3 Management Options: Evidence Assessment

Managed Aquifer Recharge (MAR) encompasses a spectrum of interventions to supplement natural recharge, from check dams and percolation ponds to infiltration basins and injection wells. Tamil Nadu has a long indigenous tradition of tank-based water harvesting — with over 39,000 traditional water bodies historically documented — that served both irrigation and groundwater recharge functions. The systematic restoration and expansion of this tank network offers one of the most geographically appropriate and cost-effective strategies for augmenting recharge in the state's hard-rock terrain (Singh & Panigrahy, 2011; Kumar, 2012) [24, 14]. Agricultural MAR (Ag-MAR), the deliberate flooding of agricultural fields during off-season periods or monsoon surplus events, has shown promising results in comparable Indian and global contexts, with modelling assessments suggesting that systematic Ag-MAR across 10–15% of irrigated area in the Cauvery delta could partially offset annual depletion in adjacent shallow aquifer systems.

Demand-side interventions represent the complementary pillar of groundwater sustainability. Conversion from flood to drip or micro-sprinkler irrigation has demonstrated water savings of 30–50% for sugarcane and vegetable crops, while the System of Rice Intensification (SRI) employing intermittent irrigation rather than continuous ponding has achieved yield improvements of 15–30% alongside reductions in water use of 20–40% in Tamil Nadu field trials (Doll *et al.*, 2014) [7]. State schemes, including the Tamil Nadu Micro Irrigation Scheme (TNMIS) and the centrally sponsored Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), have expanded micro-irrigation coverage substantially, though adoption remains constrained by high upfront capital costs and access to affordable credit among smallholder farmers.

Tamil Nadu has been among the more progressive Indian states in groundwater regulation, having enacted the Tamil Nadu Groundwater (Development and Management) Act (2003), which empowers the Groundwater Authority to regulate extraction in notified over-exploited areas. However, implementation and enforcement remain partial, particularly in agricultural areas outside formally regulated zones (Vorosmarty *et al.*, 2010) [26]. Community-based Participatory Groundwater Management (PGM) models have demonstrated that farmer collectives can effectively self-regulate abstraction when provided with transparent aquifer health information and equitable governance structures. At the national scale, India's Atal Bhujal Yojana scheme provides financial incentives for groundwater recharge and participatory management in designated over-exploited aquifers, including several in Tamil Nadu; alignment of national programmes with state-level land use planning and climate adaptation finance represents a governance priority.

4.4 Strengths and Limitations of Existing Evidence

The evidence base synthesised in this review has notable strengths. The multi-source corroboration of groundwater

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depletion across GRACE-FO, CGWB well records, and InSAR subsidence provides a robust, internally consistent picture that is unlikely to be overturned by additional data. The breadth of geospatial methodologies now applied to the Tamil Nadu context has expanded substantially since 2018, and the increasing availability of open-access satellite data (particularly Sentinel-1 and -2) and cloud computing platforms (Google Earth Engine) has democratised access to these tools for researchers in Indian institutions.

Limitations are also significant. The CGWB monitoring well network is spatially uneven, more densely distributed in accessible agricultural plains than in hard-rock upland areas, and many wells are monitored at only quarterly intervals, missing sub-seasonal dynamics critical for understanding recharge efficiency. The coarse spatial resolution of GRACE-FO (~300 km) is a fundamental constraint for basin-scale analysis in a geographically diverse state like Tamil Nadu (~130,000 km²). Most included hydrological modelling studies calibrate against historical observed data and apply CMIP5 forcing, rather than the more recent CMIP6 scenarios, introducing potential outdatedness in future projections. The social and economic dimensions of groundwater–agriculture interactions, farmer decision-making, equity in water access, and livelihood vulnerability remain systematically underrepresented in what is predominantly a biophysical literature.

5. Implications and Future Directions

5.1 Implications for Practice and Policy

The reviewed evidence carries immediate and actionable implications for agricultural and water management practices in Tamil Nadu. At the farm scale, the transition from flood irrigation to drip and micro-sprinkler systems, supported by soil moisture sensing and ET-based scheduling, represents the single most impactful demand-side intervention available, particularly for sugarcane, which accounts for a disproportionate share of groundwater extraction in certain districts. The SRI's demonstrated capacity to simultaneously improve rice yields and reduce water consumption by up to 40% positions it as a critical climate adaptation technology that merits far more aggressive policy promotion and subsidisation than it currently receives.

At the watershed scale, the rehabilitation of the state's extensive but degraded tank irrigation network serves a dual function as a MAR infrastructure and a surface water buffer that reduces monsoon runoff losses. Integrating tank restoration into the National Watershed Development Programme and climate adaptation finance streams — including potentially the Green Climate Fund — would align infrastructure investment with hydrological benefit. Spatially explicit groundwater potential zone maps, produced using multi-criteria GIS analysis integrating geology, soil, slope, land use, and rainfall data, provide the targeting intelligence needed to prioritise recharge interventions where aquifer characteristics make them most effective.

At the policy and governance scale, the most urgent implication is the need for basin-level groundwater management plans that operationalise Tamil Nadu's existing regulatory framework into enforceable, spatially differentiated extraction limits. Geospatial research — particularly the integration of GRACE-FO downscaling with high-density CGWB well monitoring — can provide the real-time aquifer health information that transparent, community-accountable governance requires. The Atal Bhujal Yojana framework provides a national template, but its effective implementation in Tamil Nadu requires stronger convergence with state-level agricultural support programmes, credit systems, and land use planning.

5.2 RESEARCH GAPS AND FUTURE RESEARCH NEEDS

Despite the substantial body of knowledge synthesised in this review, several critical research gaps constrain the development of evidence-based, spatially robust groundwater–agriculture management in Tamil Nadu. These gaps span modelling frameworks, observational infrastructure, methodological integration, and governance dimensions. Table 3 summarises identified gaps alongside proposed research directions and indicative priority levels.

Table 3. Key Research Gaps and Proposed Future Directions for Groundwater–Agriculture Research in Tamil Nadu

Gap Domain	Specific Deficiency	Proposed Direction	Priority
Coupled modelling	No high-resolution integrated climate–GW–crop models exist for Tamil Nadu	Develop SWAT-MODFLOW-Aqua Crop coupled frameworks for key basins, forced by CMIP6 projections	High
Remote sensing application	Limited SAR, InSAR, and ML-based GWL prediction tools at the state level	Scale up Sentinel-1 monitoring; integrate GRACE downscaling with high-resolution GIS platforms	High
Data infrastructure	Sparse monitoring well networks; unreported GW abstraction; incomplete crop water use data	Expand real-time telemetric CGWB monitoring; establish open-access hydrological data platforms.	Very High
Socio-economic integration	Biophysical models rarely incorporate equity considerations or farmer decision-making.	Mixed-methods approaches combining household survey data with hydrological model outputs.	Medium
Coastal groundwater	Saltwater intrusion dynamics and sea-level rise scenarios are understudied at the basin scale.	Variable-density solute transport models coupled with IPCC SSP sea-level scenarios	High
ML-driven forecasting	Lack of validated AI tools for seasonal GWL and crop yield forecasting in Tamil Nadu	Transfer-learning frameworks adapted from national and global datasets to Tamil Nadu contexts.	Medium–High

Note. Priority levels reflect the convergence of gap severity, feasibility of resolution, and potential policy impact as assessed across the reviewed literature. GW = groundwater; SSP = Shared Socioeconomic Pathway; GWL = groundwater level.

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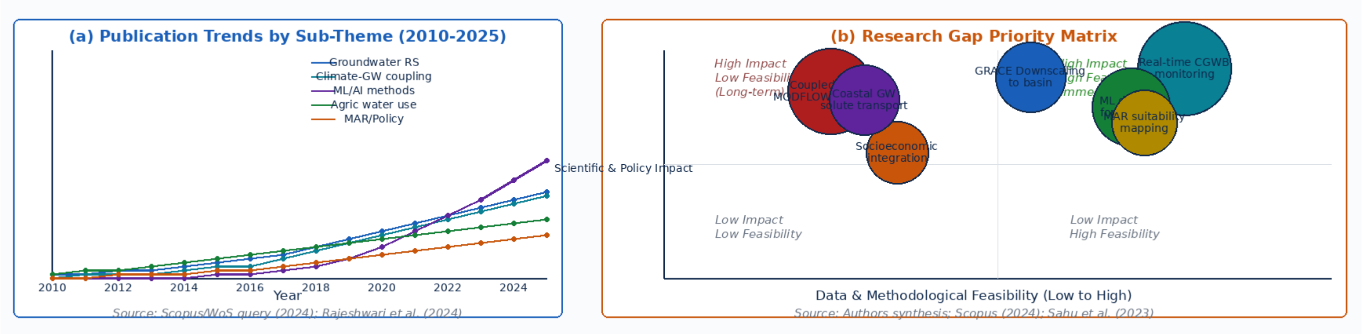
The most pressing methodological need is for high-resolution, fully coupled climate–groundwater–crop models applicable to Tamil Nadu's principal river basins. Current assessments either simulate surface hydrology (SWAT) or groundwater dynamics (MODFLOW) in isolation, or couple them without dynamic crop growth feedbacks. Integration of crop growth models such as AquaCrop or DSSAT within SWAT-MODFLOW frameworks, forced by dynamically downscaled CMIP6 projections, would enable scenario-based assessments of the combined effect of climate change and management interventions on food production and groundwater sustainability across the decadal timescales relevant to policy planning.

Equally critical is the expansion of the observational data infrastructure that underpins both model calibration and direct operational monitoring. Transition to automated, telemetry-equipped data loggers — already initiated under national groundwater monitoring programmes — would substantially improve the temporal resolution and spatial density of groundwater level records. Complementing this with open-access data-sharing platforms linking CGWB, state agencies, universities, and research institutions would unlock analytical capacity currently constrained by institutional data silos.

From a social science perspective, the human dimensions of groundwater–agriculture dynamics in Tamil Nadu remain poorly understood within the reviewed literature. How farmers make irrigation decisions under climatic and economic uncertainty, how progressive aquifer depletion interacts with agrarian distress and rural outmigration, and how regulatory and subsidy interventions are received by diverse farming communities are questions requiring interdisciplinary approaches combining quantitative hydrological modelling with qualitative ethnographic and survey methods.


(a) Publication Trends by Sub-Theme (2010-2025)

Source: Scopus/WoS query (2024); Rajeshwari et al. (2024)

(b) Research Gap Priority Matrix

Source: Authors synthesis; Scopus (2024); Sahu et al. (2023)

Fig 8: Bibliometric trend analysis and research priority matrix for Tamil Nadu groundwater–agriculture studies:

Figure 8. Bibliometric trend analysis and research priority matrix for Tamil Nadu groundwater–agriculture studies: (a) cumulative publication trends (2010–2025) by sub-theme derived from Scopus and Web of Science query results; (b) research gap priority matrix positioning identified gaps according to scientific and policy impact (y-axis) versus data and methodological feasibility (x-axis); bubble size indicates estimated research effort requirement. Sources: Scopus database query (2024); Rajeshwari *et al*. (2024) [19]; Sahu *et al*. (2023) [21].

6. CONCLUSION

This systematic review has synthesised the current state of knowledge on the geospatial assessment of climate variability impacts on groundwater resources and agricultural productivity in Tamil Nadu, drawing on 67 primary peer-reviewed studies published between 2018 and 2026. Several overarching conclusions emerge from this synthesis that carry significance both for the scholarly community and for policy practice.

First, the evidence for climate-driven groundwater depletion in Tamil Nadu is robust, internally consistent, and multi-sourced, converging across GRACE-FO satellite gravity observations, CGWB monitoring well records, hydrological model simulations, and SAR-based land subsidence mapping. The Cauvery delta and Chennai coastal aquifer are the most acutely stressed systems, while hard-rock aquifers of the interior plateau exhibit more geographically dispersed but structurally significant decline. All assessed CMIP6 climate scenarios project an intensification of these depletion trends under both moderate and high emissions pathways.

Second, the agricultural consequences of groundwater depletion are already manifest and economically significant: rising irrigation energy costs, systematic crop area substitution away from water-intensive rice, declining yields in groundwater-dependent zones, and heightened vulnerability of smallholder livelihoods to compound drought–heat stress events. These impacts are not merely hydrological; they are deeply socio-economic and demand integrated policy responses addressing both the biophysical and institutional dimensions of water insecurity.

Third, the geospatial and remote sensing toolkit available for assessing these dynamics has advanced substantially during the review period. GRACE-FO-based groundwater monitoring, Sentinel-2 crop stress assessment, SWAT-MODFLOW coupled modelling, and machine learning groundwater forecasting each contribute distinct and complementary analytical insights. Their synthesis within an integrated, operational monitoring and decision-support framework specific to Tamil Nadu represents both the most important methodological opportunity and the most significant gap in the current literature.

Fourth, management interventions that demonstrably reduce groundwater stress, including agricultural MAR through tank

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rehabilitation, drip irrigation adoption, the System of Rice Intensification, crop diversification, and community-based participatory groundwater governance, are well-documented in the reviewed evidence base and technically feasible at scale. However, their large-scale implementation requires overcoming entrenched barriers of cost, institutional fragmentation, and data poverty. Geospatial research has a central and indispensable role in making the case for these interventions through quantified, spatially explicit evidence of their hydrological effectiveness and agricultural co-benefits.

Ultimately, sustaining Tamil Nadu's agricultural water security under accelerating climate change demands a convergence of scientific rigour, technological innovation, institutional reform, and sustained community engagement. This review is intended to serve as a comprehensive scholarly foundation for the researchers, practitioners, and policymakers pursuing that convergence.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

This review article does not report original empirical data. All datasets cited are publicly available as referenced in the text. GRACE-FO data: https://grace.jpl.nasa.gov. IMD gridded rainfall data: https://imdpune.gov.in. CGWB well monitoring data: https://cgwb.gov.in.

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